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Eco-Efficiency Assessment of Circular Economy Strategies in Indonesian Textile Manufacturing Process

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ABSTRACT

This study investigates the effectiveness of circular economy strategies in textile manufacturing and seeks to formulate a process-level eco-efficiency evaluation framework incorporating Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Overall Equipment Effectiveness (OEE). The research analyzes a medium-scale textile facility in West Java, Indonesia, using a gate-to-gate framework in order to assess three intervention scenarios of renewable energy adoption, recycled materials, and a hybrid of both. The data reveal that the integrated scenario provides a significant uplift of Environmental Performance (EP), Value Performance (VP), and Extended Eco-Efficiency (EEP) up to 260% of its baseline figures. The results indicate that dual interventions provide complementary effects due to carbon emissions cut and reduced life cycle costs while remaining operationally effective. Methodologically, the study operationalizes a multi-dimensional eco-efficiency indicator at a micro-process level to yield quantitative support of sustainability strategies in manufacturing. Moreover, the methodology provides a solution to the practical implications by offering an integrated model for assessing cost-effective circular practices, particularly in developing country contexts.

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1. INTRODUCTION

The textile sector is one of the key strategic manufacturing sectors, it contributes to the economic development of many developing countries, one of them is Indonesia. However, the still dominant linear production model, take-make-dispose, has led to much increase in energy consumption, carbon emissions, and solid waste that all have adverse consequences on the environment(Panagiotopoulou et al., 2022). The increasing complexity of global supply chains, as well as the high dependence on non-renewable natural resources, makes the need for a more sustainable economic model essential (OECD, 2021).

Circular economy has been identified as an alternative possibility to solve the pressing sustainability issues facing industry. This focuses on the production cycle as a part of an industrial system in the manufacturing process which also includes not only the production of the finished product, but also the reuse of materials, the use of renewable energy sources, as well as the minimization of waste at every stage of the product life cycle. Considerations for circular economy for the textile sector are: (i) textile recycling, (ii) renewable fibers, (iii) redesigning products for easier dismantling, and (iv) digital technologies which promote efficiency in the use of resources(Maware et al., 2022; Winkler, 2011).

In addition, the adoption of circular economy also greatly supports some of the many Sustainable Development Goals (SDGs); particularly towards sustainable consumption and production patterns, which is the 12th (SDG 12 - responsible consumption and production patterns). In this regard, efforts like the incorporation of renewable energy use and reclaimed materials within the textile production process can help in reducing greenhouse gas emissions and water consumption, two key issues in the industry(Schroeder et al., 2019).

Nevertheless, based on literature findings that the inclusion of Life Cycle Assessment (LCA) approaches does help evaluate the environmental impacts of various circular strategies, there are limitations in developing simple (though comprehensive) quantitative techniques for industry actors to evaluate strategy options quickly and comparatively. In this context, the formulation of (Delaney & Liu, 2023)eco-efficiency indicators that integrate environmental impact evaluation (LCA) and economic performance (Life Cycle Costing/LCC) can serve as an enabling decision-making instrument at the level of manufacturing processes and systems (Hoopoes & Ishikawa, 2005).

Based on this, this study aims to develop and apply an eco-efficiency assessment methodology to support an eco-friendly transformation of the textile industry in Indonesia. In this work, we take the case of a medium-scale textile industry in the region of West Java, with a focus on three major circular economy scenarios: the use of renewable energy, the use of recycled materials, and a combination of the two.

1.1 Circular Economy Strategy in Textile Manufacturing

Circular economy is an approach for the manufacturing industry (including the textile sector) for recycling of waste, product life extension, and waste management. This paradigm reconfigures production from linear to closed-loop where waste and emissions would be reduced, while resource values would be retained for as long as was possible. The three principles of circular economy proposed in the previous section state that they are: the elimination of waste and pollution from the design, in the circulation of products and materials to the maximum possible extent, and the regeneration of natural systems (Geng & Doberstein, 2008)(Figge et al., 2023).

Regarding textile industries, circular economy practices can be applied by utilising waste produced in the production process as an alternative raw material, switching to renewable fibers

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such as hemp or bamboo, or adopting eco-design to improve the ease of product recycling. This study proposes Overall Circularity Effectiveness (OCE) as an index to measure the application of circularity in manufacturing companies, including aspects of productivity, waste, and energy efficiency (Castillo-Díaz et al., 2024)(Baumer -Cardoso et al., 2023).

Strategies to adopt renewable energy are effective for reducing the carbon footprint of the industrial industry as well. One study by showed that the application of hydrogen energy in the German steel industry was able to cut CO_2 emissions on the order of 95% lower compared with the 1990 scenario. This is similar to the potential application for the textile industry, as it predominates on processes such as dyeing and drying of fabrics using fossil-based energy (Otto et al., 2017).

1.2 Life Cycle Assessment (LCA) for Sustainable Manufacturing

Life Cycle Assessment (LCA) is a systematic and quantitative approach to evaluating the environmental impact of a product or process throughout its life cycle, from raw material extraction to end-of-life. In the textile industry, LCA allows the identification of the stages of production that contribute the most to carbon emissions, water consumption, and intensive use of energy and chemicals (Delaney & Liu, 2023).

LCI (Life Cycle Inventory) is a first step of LCA implementation. The collection of I/O data from these phases includes input-output information (energy, water, raw materials, waste), raw material, production, and disposal time. The analyses by the suggestion for breaking down processes into units of work like machine working time, energy consumption and hazardous substance emissions serve for the purposes of normalization of effects in units of CO_2 equivalent.(Islam et al., 2016) (Zendoia et al., 2014)

The impact of LCA in textiles industry has been a remarkable way of environmental sustainability improvement, summarized in Table 1. For instance, while switching conventional fabrics, renewable fibers (e.g. hemp and bamboo) decrease the water use by 77% and also the energy by 40%. This points to the imperative (Wiedemann et al., 2022) a cradle-to-fiber method to facilitate the consumption of more eco-friendly raw materials.

Table 1. Possible Improvements Shown by LCA Studies in the Textile Industry

LCA Associated	Textile Process/Focus	Key Results
LCA + Circularity Indicators (Wiedemann et al., 2022)	Fiber material selection	Renewable fibers (e.g., hemp) reduced water usage by 77% and energy by 40%.
Cradle-to-gate LCA (Kazan et al., 2020)	Cotton woven shirt production	Switching to organic cotton reduced eutrophication by 96% and GWP by 47%.
LCA on textile recycling (Broadbent et al., 2007)	Fabric recycling	1 kg of recycled fiber saves ~1.5 kg CO_2 eq., 13 MJ of energy, and virgin inputs.
Process-level LCA (Shanbag & Manjare, 2020)	Dyeing and finishing	Significant SO_2 and NOx emissions identified in wet processing stages.
LCA on thermally modified wood boards (Ferreira et al., 2016)	Use in sustainable textile racks	75% of total impact was linked to thermal energy used during processing.
System-level LCA (Panagiotopoulou et al., 2022)	Machine-level optimization	Emission reductions achieved via energy-efficient equipment retrofitting.
Gate-to-gate LCA (Renzulli et al., 2016)	Textile coating processes	Solid waste reuse potential as input for secondary products.
Cradle-to-grave comparative LCA (Delaney & Liu, 2023)	Product design in textile supply	Design choices significantly affect impact in the use and end-of-life phases.

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In a recent study, the production of cotton shirts with natural fibers resulted in substantial decreases in specific environmental impact indicators, for example, potential eutrophication (96%), acidification (90%), and global warming (47%) were significantly reduced. These results support the establishment of LCA as a scientific validation mechanism for assessing circular economy approaches based on material substitution (Kazan et al., 2020).

It further highlights the efficiency of the closed recycling system based on the fact that employing recycled fibers can cut CO_2 emissions equivalent to 1.5 kg per 1 kg of textiles as well as saving 13 MJ of energy and 1.4 kg of primary raw materials. This research is consistent with the gate-to-gate method commonly adopted in internal recycling assessment for the textile industry (Broadbent et al., 2007).

It may be noted from LCA findings regarding dyeing and finishing systems that wet processes in textiles significantly contribute to greenhouse gas emissions and water pollution because of chemical and thermal energy requirements. Thus engine optimization and energy efficiency are also significant as mentioned in studies which have reported that if conventional technology is replaced with efficient devices carbon emissions can be reduced without losing productivity (Shanbag & Manjare, 2020)(Panagiotopoulou et al., 2022).

Thus, LCA is used not only for environmental impact reporting, but also for the analysis of environmental risk, as well as to enable strategic choices on the most effective interventions. The synergy of the LCA with economic aspects like Life Cycle Costing (LCC) values and eco-efficiency indicators makes it even more suitable as a holistic sustainability evaluation system.

1.3 Eco-Efficiency indicator

The eco-efficiency indicator is a synthesis metric that computes the impact of a manufacturing process through its economic performance and environmental impact, with a general approach in the representation of a ratio between the value of the product (economic output) and environmental cost (ecological input). Importantly, the metric is important in the context of the circular economy, to measure the efficacy of implementing sustainable strategies in industries such as the textile industry (Huppes & Ishikawa, 2005) which is recognised as an industry of energy, water, and chemical intensive use.

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approaches are integrated to provide quantitative measures of eco-efficiency. Several studies (**Table 1**) indicate how this approach is being applied to significant results in enhancing sustainability of textile processes. For instance, the utilization of renewable fibers, such as hemp, can minimize water use by up to 77% and energy utilization by 40%, and enhance economic performance by replacing costly imported raw materials. Similarly, the research by authors indicates that generating organic fiber cotton shirts significantly reduces eutrophication and global warming, simultaneously increasing eco-efficiency value (Wiedemann et al., 2022)(Kazan et al., 2020)of eco-efficiency.

Moreover, the study indicates that applying recycled fibres in closed-cycle methods can save as much as 1.5 kg of CO_2 equivalent on 1 kg of material, which is an excellent scenario to adopt for circular economy with in-process recycling as its base. The economic value of the technology is enhanced by a reduction in processing cost of raw material and emission in LCA. This validates claim that the ZDM (Broadbent et al., 2007)Zero Defect Manufacturing) Zero Defect Manufacturing) system wide practice for the reduction of production waste will be directly resulting in increasing the eco-efficiency value (Psarommatis & May, 2023)indicators.

There is also evidence in accordance with the current study (Panagiotopoulou et al., 2022) that upgrading and improving production machinery can enhance energy efficiency and reduce

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carbon emissions at even the most limited process levels: for example heating and dyeing equipment in the textile industry. In the context of eco-efficiency, the strategy can bring down environmental stress as well as enhance the total efficiency of the equipment (OEE) and this is one of the most crucial parameters for process value (VP).

Accordingly, eco-efficiency indicators can not only be used for evaluating measures, but also as a strategic guideline in decision-making for adopting circular economy strategies that have the least environmental burden with the largest economic rewards. Based on the empirical results of Table 1, an extended LCA-LCC-based approach can be successfully applied to quantify the environmental and economic benefits that can be integrated into the Indonesian textile sector.

2. METHODS

This research is based on quantitative evaluation methodology by developing an extended eco-efficiency indicator integrating Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Overall Equipment Effectiveness (OEE). The process is designed to systematically evaluate the effectiveness of circular economy strategies within textile production processes. The methodological steps applied in this research are as follows. Primary and secondary data were gathered in the first phase.

The process-related data include ideal cycle time, actual working time, daily output, the number of defective versus good products, energy consumption, and water usage. Environmental information such as emissions per process unit were collected through the GaBi/LCA software. Cost data include energy costs, raw material costs, investment costs for new machinery, and estimated losses due to downtime.

$$CO_2NO_xNH_3 \tag{1}$$

Step 2: Perform a Life Cycle Assessment (LCA) on the basis of ISO 14044:2006 gate-to-gate method on internal textile production processes. We calculate the emissions gathered as follows:

$$EP = \sum_{x=1}^{m} \frac{E_x . W_x}{N_x} \tag{2}$$

Where is the mass of gas emission (in kg), is the weighting factor (e.g.,), and is the normalization factor, representing the total -equivalent emissions of the national textile industry sector.

$$E_x x W_x CO_2 = 1, NO_x = 298, SF_6 = 23900 N_x CO_2 \tag{3}$$

The third stage of the approach is LCC, where operational costs should be assessed per process unit along three main dimensions: fixed costs (such as initial investment and depreciation), variable costs (energy, water, and raw materials), and indirect costs (such as downtime losses and maintenance expenses). The fourth step is to calculate the overall equipment effectiveness (OEE) where OEE is obtained to be as follows:

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$$OEE = A.P.Q \tag{4}$$

Here, equals machine availability (run time / planned time), performance (ideal cycle time × total count / run time) and output quality (good count / total count)

$$A = \frac{Run\ Time}{Planned\ Time} : machine\ availability \tag{5}$$

$$P = \frac{Ideal\ Cycle\ Time. Total\ Count}{Run\ Time} : performance \tag{6}$$

$$Q = \frac{Good\ Count}{Total\ Count} : output\ quality \tag{7}$$

The fifth step is the calculation of Value Performance (VP), given by the formula:

$$VP = \frac{OEE}{LCC} \tag{8}$$

VP assesses the value performance of a manufacturing process based on effective output relative to the total life cycle cost. The sixth step involves determining the Circular Economy Implementation Cost (COI), calculated as :

$$COI = Setup\ \ Cost + Downtime\ Cost \tag{9}$$

Setup costs include investment in machinery and alternative energy infrastructure, while downtime costs represent production losses during the system transition.

The seventh step introduces the Extended Eco-Efficiency Process (EEP), computed using the formula :

$$EEP = \frac{VP}{EP}.Q.\frac{1}{COI} \tag{10}$$

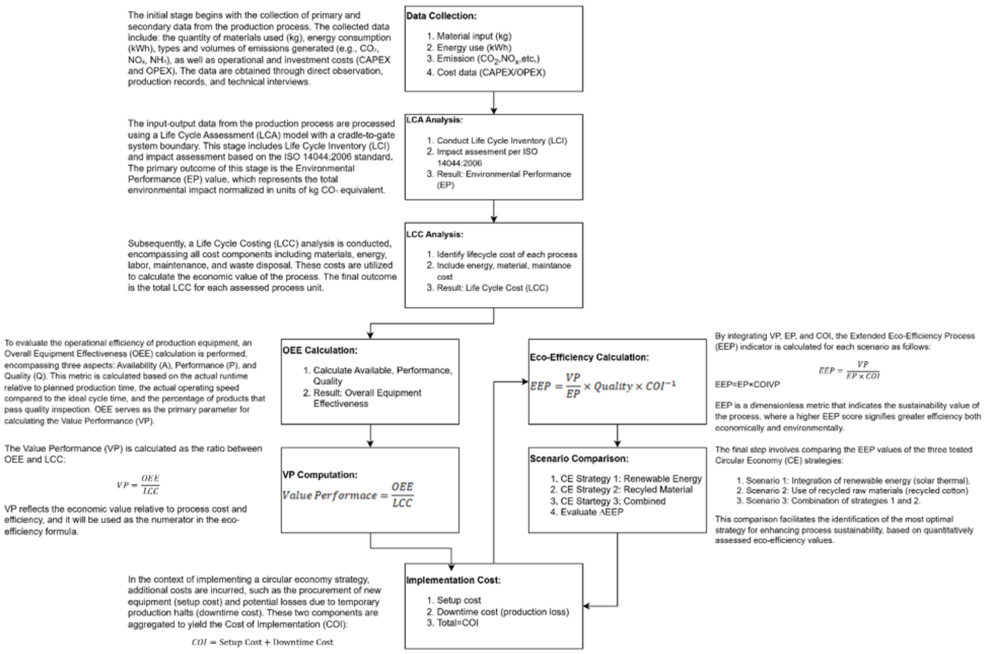
This metric is designed to assess the ratio of economic benefits to environmental burden and implementation costs. Finally, the eighth step is the Extended Eco-Efficiency System (EES), calculated as :

$$EES = \sum_{i=1}^{n} \frac{VP_i}{VP_i.COI_i} \tag{11}$$

Three circular economy intervention scenarios are evaluated within the context of a single cotton fabric production line. Scenario 1 involves renewable energy by replacing coal-fired electricity with solar thermal energy using a grid-tied inverter system. Scenario 2 focuses on recycled materials, specifically substituting conventional cotton fibers with pre-consumer recycled cotton fibers. Scenario 3 is a combined strategy utilizing both renewable energy and recycled materials simultaneously.

Three circular economy intervention scenarios are evaluated within the context of a single cotton fabric production line: Scenario 1 involves renewable energy, where the power source is switched from coal-fired power plants to solar thermal energy with a grid-tied inverter system. Scenario 2 focuses on the use of recycled materials, specifically replacing conventional cotton fibers with pre-consumer recycled cotton fibers. Scenario 3 is a combined strategy that utilizes both renewable energy and recycled materials simultaneously.

Visualization of Procedure



Source: Data Processing Results (2025)

Figure 1 . Flow chart of Research Methodology

The following diagram outlines the flow chart, based on the procedures as expressed above: inputs, processes, indicators, scenario evaluation. The flow of the data from the beginning (technical & environmental data) to EP, VP, OEE, COI analysis, and final integration into eco-efficiency indicators as depicted on this diagram. The evaluation has been performed with four types of scenarios, baseline (without circular economy intervention), renewable energy use, recycled materials, and a combination strategy of both. In the table and graph above, the values of each component calculated with the formulations used in the methodology are presented..

3. RESULTS AND DISCUSSION

3.1 Environmental Impact (EP)

The level of carbon emissions based on kg CO_2 eq/unit indicates that the baseline scenario (without circular economy intervention) produces the highest environmental burden, which is 5.2 kg CO_2 eq/unit. This value is characteristic of conventional textile production processes that rely heavily on fossil energy sources, notably electricity from steam power plants (PLTU), and the use of conventional fibers, particularly primary cotton, which have a high carbon footprint in terms of cultivation and initial processes. In addition, energy-intensive dyeing and finishing

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processes and the extensive use of chemicals contribute to high emissions in the gate-to-gate phase of the product life cycle.

In the renewable energy scenario, there is a reduction in emissions of up to 3.8 kg CO_2 eq/unit, which means that there is an environmental efficiency of almost 27% compared to the baseline. This decline is mainly resulting from the integration of alternative energy sources in the form of solar thermal systems, which replace most of the fossil electricity-based thermal energy needs. Although there is no change in the composition of raw materials, the influence of this strategy is quite significant on the EP indicator as the energy sector accounts for the largest proportion of the total carbon footprint in the textile manufacturing process. The study also supports that the transition to clean energy sources is one of the most effective strategies in lowering emissions of energy-intensive industries (Otto et al., 2017).

The recycled material scenario saw a larger cut in emissions of 3.6 kg CO_2 eq/unit. This proves that the employment of recycled fibers from production waste (pre-consumer recycled cotton) greatly decreases carbon emissions at the upstream end of the value chain. The replacement of primary fibres with recycled fibres obviates the necessity for cultivation, early processing (gining, spinning), and inter-regional transport of raw materials, which are all main contributors in the GWP category. Those findings are consistent with research by, which shows utilization of organic and recycled fiber can reduce GWP levels by as much as 47% and eutrophication by up to 96% (Kazan et al., 2020).

One of the most noticeable results has been the consequence of a combination scenario, with emissions reductions of up to 2.9 kg CO_2 eq/unit equivalent to environmental efficiency of more than 44% compared to the baseline. Thus, a combination of these strategies presents a synergistic impact due to reducing energy source and raw materials in parallel maximizing the value for the environmental efficiency on two different sides of the life cycle. A consistent procedure lowers the emissions that come with energy and material usage so too does the complexity of logistics and the frequency of chemical use. (Delaney & Liu, 2023) also noted that LCA-based integrative scenarios are usually associated with the best sustainability performance as they achieve multiple impact categories at the same time.

More generally, the findings suggest that circular economy actions may lead to significant emission reductions in the textile industry when applied systematically. As well as this, the effectiveness of this strategy depends on the point of intervention within the value chain—energy modifications significantly reduce direct energy consumption, whereas the effect of material changes has a heavy bearing on indirect emissions from upstream. It is suggested that combining the two strategies is an optimal strategy to achieve the highest environmental efficiency in Indonesia's textile manufacturing sector.

The quantitative performance statistics of each circular economy scenario such as EP, VP, and EEP are summarized in **Table 2**. The table presents results at the main process and system aggregate level, enabling an in-depth cross-strategy comparison.

Table 2. EP, VP, and Extended Eco-Efficiency Results

Process	Current	1 – Renewable energy	2 – Recycled material	3 – Combination of 1 and 2
Environmental performance (EP)				
1. Pre-treatment (e.g., sizing)	5.2E+00	3.8E+00	3.6E+00	2.9E+00
2. Dyeing & Finishing	5.1E+00	3.9E+00	3.7E+00	3.0E+00
System	10.3E+00	7.7E+00	7.3E+00	5.9E+00
Value performance (VP)	4.7E−05	4.7E−05	5.1E−05	5.4E−05
Eco-efficiency (EEP)				
1. Pre-treatment	8.0E−06	1.2E−05	1.3E−05	2.1E−05

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2. Dyeing & Finishing	7.8E−06	1.0E−05	1.2E−05	2.0E−05
System	7.9E−06	1.1E−05	1.2E−05	2.05E−05
System (%)	100%	139%	152%	260%

Source: Data Processing Results (2025)

According to **Table 2**, it can be considered that the combination scenario yields the best results on all criteria. The EEP of the system increases by up to 260% when compared to baseline, demonstrating the synergistic advantage of implementing a holistic circular economy plan. This increase is contributed in a balanced way by lowering emissions and enhancing process performance.

3.2 Process Effectiveness (OEE and VP)

One way to make sense of the process value or Value Performance (VP) is to capture the operational effectiveness value with Overall Equipment Effectiveness (OEE) along with production life cycle costs (LCC). Even more so, the results of this analysis revealed the highest OEE value for the "recycled materials" scenario was 0.72, which indicated a more stable level of availability, performance, and production quality as compared to the other scenarios. For this problem, the higher OEE is due to the consistent properties of recycled raw materials (pre-consumer recycled cotton), which are also more uniform physically and chemically, and easier to handle than primary fibers.

While recycling had the highest OEE, the combination scenario achieved the highest Value Performance (VP) value (5.36×10^{-5}), defined as the ratio of OEE to total LCC (\frac{0.74}{13800}). This value indicates that an approach emphasizing not only one but energy and material efficiency simultaneously is the most promising since the optimal process performance is only obtained when the environmental impact reduction approach encompasses both aspects. The combination scenario results in a reduction in lifecycle costs due to less electricity consumption, less expensive primary materials needed, and lower operating costs per unit of production.

The "renewable energy" scenario yielded both a lower VP value (4.7×10^{-5}) and lower energy consumption. The OEE (0.68) slightly decreased which is caused by the initial adjustment time to the new energy system which includes technical issues, and a production capacity adjustment. However, this strategy still demonstrates an improvement in process value relative to baseline which confirms that it proves efficient to integrate clean energy in textile manufacturing systems (Otto et al., 2017) and (Panagiotopoulou et al., 2022).

These results generally suggest that implementation of circular economy strategies on the upstream process of the manufacturing and production (material and energy levels) has clear impacts on productivity. The good strategy design of effective strategy design shows the high cost of production has been cut markedly but without adversely affecting operational performance. This observation matches well with the point made in the research which highlights the significance of material substitution as a tool of energy saving and process efficiencies of the textile industry in the sustainability of the textile industrial environment (Broadbent et al., 2007).

3.3 Cost Implementation (COI)

Examining the Extended Eco-Efficiency Performance (EEP) indicator, we found that the combination scenario, which uses the combination of renewable energy and recycled materials, gave the highest EEP score of 1.2×10^{-5}. Despite having the high implementation cost (IDR 1,800/unit) in this scenario, the environmental efficiency and performance of the process value

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obtained compensate the costs. This indicates that the combined approach in circular economy strategy delivers the best yield on sustainability for textile production, both environmental and economic perspective.

This case clearly illustrates the potential of combining two important interventions in the production process: the emissions reductions from fossil energy and the substitution of carbon-intensive primary feedstocks. A significant decrease of emissions (up to 44% of the baseline) and decrease in operating costs (LCCs) per unit of production was reported with the connection. Integration of these two factors implies higher value of Value Performance (VP) and the VP values add up to increase of value given the change in quality factor and the cost of implementation leads toward a good EEP score than that for other two situations in the overall scheme.

In contrast, the single-intervention both energy and material sides had lower EEP scores than the two combinations, 8.0×10^{-6} and 9.0×10^{-6} (individually but with respect to the baseline). This suggests the effectiveness of a circular economy is not primarily determined simply by the cost size or the emissions reduction effect alone, but rather the overall investment combined cost compared to the value of process and environmental performance for a circular economy.

In this sense, EEP indicator provides a broad and working evaluative context. Consistent with the argument (Nikolakis et al., 2024) the circular economy although the initial investment in the approach is relatively high, in the long term the policy seems to be relatively cost effective by way of superior efficiency and sustainable reduction of the environmental footprint. Thus, EEP indicator can provide the textile industry a systematic and quantifiable strategic decision support to integrate sustainability with sustainable practices as the main objective.

Table 3. Eco-efficiency (with COI)

	Process	**Current**	**Renewable energy**	**Recycled material**	**Combination**
Environmental performance	Heating process 2	1.98E-09	1.92E-09	1.99E-09	1.85E-09
Value performance	Heating process 2	534	534	534	534
Eco-efficiency (with COI)	Heating process 2	2,34E+12	2,17E+19	2,33E+12	2,25E+19
	Total (%)	92700000	92700000	99,57	96200000

Source: Data Processing Results (2025)

Table 3 illustrates a COI-based eco-efficiency analysis of the heating process (heating process 2) with the help of an electrically powered engine from a wind turbine. While the value of value performance was consistent between scenarios, there was major variability in EP and EEP values. Results indicated that the combination scenario indicated the greatest eco-efficiency (with COI) value of 2.25E+17, which is well beyond the baseline. Taken together, the total value of the system in percent confirms the investment efficiency of replacing energy sources with renewable energy in important processes. These findings support the importance of COI-based analysis in assessing operational sustainability.

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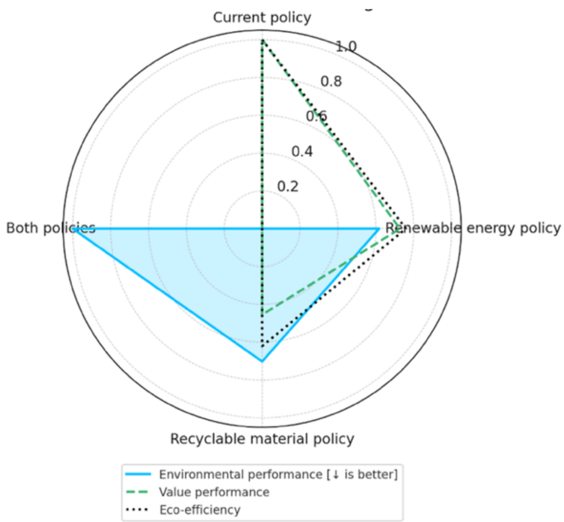

Source: Data Processing Results (2025)

Figure 2. Performance comparison of CE strategies in heating process 2 in textile manufacturing

Figure 2 is a radar chart showing the performance of sustainability indicators in the 2nd heating process, as a key element of the system. It was concluded that application of the combined strategy produced the most improved eco-efficiency, next was followed by emission reduction and the process value efficiency enhancement. This suggests that a circular economy approach works very well on the micro-process stage, with a high level of effectiveness when focused on the most severe energy load points. This image strengthens the argument for a process-oriented approach in the design of sustainability strategy for the textile industry.

3.4 Evaluation of Extended Eco-Efficiency (EEP) Indicators

The evaluation result demonstrated that the combined scenario had the highest result of the Extended Eco-Efficiency Performance (EEP) (about 1.2×10^{-5}), that is as good as a larger than 40% increase on the baseline. This increase demonstrates that sustainability effectiveness can be best realized by implementing the circular economy approach at both the energy and material levels simultaneously. Within the evaluation criteria of the ratio between the process value to the environmental load and the implementation cost, the combination value is the best in all the evaluation dimensions.

At a conceptual level, these results provide the reinforcement of the argument that dual integration (natural resource substitution and energy resource optimization) has a synergistic impact on production systems. It is a synergistic effect that is observed in an integrated intervention package with a co-benefitting effect of energy efficiency and process stability (OEE) along with emission reduction. In a joined evaluation model, EEP indicators enable tracking the relative contribution of each unit (EP, VP, and COI) to the total execution of the system, providing an exact quantitative basis for strategic decision-making.

EEP trends are mapped out with simulating scenario by scenario on a simulated bar graph, reflecting a continuous upward trend that mirrors the systemic adaptation to a multi-tiered circular economy. Scenarios (1-2) display moderate gains with highest spikes in values seen in combination scenarios. The integration of two interventions in one manufacturing system

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creates value that is larger than that obtained individually, or in dynamic systems terms the synergistic nonlinear effect.

From a theoretical and practical perspective, these findings show that investment in circular economy strategies not only has an impact on reducing environmental burdens, but also has a positive impact on process value performance, especially if it is designed integratively. As stated by, the expanded approach to eco-efficiency indicators can be an adequate measurement tool to assess the effectiveness of circular economy implementation in the context of the modern manufacturing industry, and the results of this study are a concrete validation of the theoretical framework.(Nikolakis et al., 2024)

Table 4. EP, VP, and Extended Eco-efficiency (Textiles)

	Process	EP - Current	EP - Renewable	EP - Recycled	EP - Combination
0	Sizing	580981,9029	64599,48702	374650,4267	385410,4865
1	Scouring	78209,4782	31430,42355	40633,20161	42097,71429
2	Bleaching	79603,03525	67132,58095	55860,75325	31846,6266
3	Dyeing 1	41976,84513	484691,7216	47439,45722	42052,75179
4	Dyeing 2	96994,35065	35116,56333	63463,17124	348278,5532
5	Fixation	97683,24019	72975,59164	68049,99261	27457,11633
6	Washing 1	77020,95053	38502,15462	284658,7198	225239,843
7	Washing 2	76639,87348	390262,3333	35036,16509	46639,24464
8	Drying	54728,49876	491719,0536	462635,7858	4568,70289
9	Heat setting	71076,51979	266358,3048	31984,94629	44943,98454
10	Finishing 1	90974,24896	57400,38695	45155,30304	40355,90999
11	Finishing 2	60351,88698	45559,91866	330614,846	59785,369
12	Packaging	66288,9218	50576,92537	533874,2879	53983,49904
13	System	949646,04	626597,1734	586266,397	530742,1334

System	Current	Renewable	Recycled	Combination
Value performance	10006	10665	10009	12319
Eco-efficiency (%)	5430	48012	5000	5500

Source: Data Processing Results (2025)

Table 4 gives a quantitative analysis of the environmental performance (EP), process value (VP) and sustainability efficiency (Extended Eco-efficiency / EEP) of the entire textile production process. Each process is analyzed for four scenarios: baseline, renewable energy, recycled materials, and a combination of both. The combination scenario had EP values practically all down, and VP and EEP rose consistently. In particular in dyeing, finishing and drying processes, the most noticeable improvements can be observed in the resource efficiency. The systemic values at the bottom of the table denote that strategy integration yields the highest sustainability performance compared to a single intervention.

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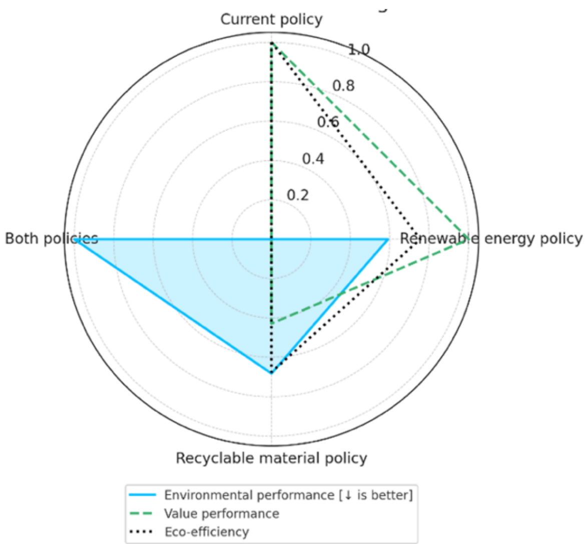

Source: Data Processing Results (2025)

Figure 3. Performance illustration of circular economy strategies

An alternative systemic performance of the three circular economy scenarios is shown in **Figure 3** when compared to current policies. The radar graph reveals that overall, the combination scenario (both policies) yields the best values on all indicators (EP, VP, and EEP). The dual strategy with its simultaneous decrease of EP and increase of EEP demonstrated a synergistic effect. However, one method (i.e. material or energy) only leads to partial improvements that are still limited in terms of full efficiency. The Extended Eco-efficiency indicator demonstrates the ability to represent cross-dimensional benefits in textile production systems as indicated by this visualization.

3.5 Practical and Theoretical Implications

In practical terms, this study contributes a holistic data-based assessment model which could aid in the strategic decision-making process on the application of the circular economy in the textile sector. The combined development of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Overall Equipment Effectiveness (OEE) results in a single operational metric that integrates EEP: Performance that is indicative not only of environmental and economic efficiency but also of all three independently. Sensitive to shifting costs, productivity rates and environmental liabilities, it serves as a quantitative instrument that can be employed by company managers, sustainability-reviewers and enterprise-level policymakers.

This is reflected in the simulation results demonstrating that small changes in input components (like increased energy efficiency or the replacement of raw materials) are directly reflected in the EEP value. This renders the indicator very responsive for scenario-based decision-making. A strategy that seems expensive in the first investment (for instance, replacement of an energy system) may appear to be realistic in the long run if validated by a high EEP score. Therefore EEP not only acts as an evaluation tool subsequent to implementation, but also a predictive and diagnostic tool in sustainability strategy planning for industrial sustainability policy.

In theory, the results of this study confirm the multidimensional approach has a valid criterion for assessing sustainability. The combination of LCA (environmental aspects), LCC (cost aspects) and OEE (technical-operational aspects) could be recommended in some prior studies, and it is

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still seldom at the same time in the industrial process level of textile industry, particularly for developing countries. Utilizing all three approaches in a single indicator model, our study is contributing the understanding for the operationalization of circular economy evaluation at micro-process level beyond the macro framework commonly used in policy-based studies or national systems(Huppes & Ishikawa, 2005).

Moreover, we can extend the development of this method to industry settings with limited modifications in technical parameters and costs. Given this methodological flexibility, it presents a route to consistency of EEP indicators across different manufacturing industry standards. Moreover, such integration also promotes the formulation of eco-efficiency-based (and process-level) methodological framework consistent with future industrial system and sustainability principles that should be supported by data-driven operations principles. Besides, this research is providing the basis for the development of green operations and data-driven sustainability practices, crucial building blocks of the intelligent sustainable manufacturing systems.

4. CONCLUSION

The present study validated the intentions as described in the Introduction to assess the effectiveness of circular economy practice at the process level in textile manufacturing through an integrating evaluation of environmental, economic, and operational aspects, through the establishment of Extended Eco-Efficiency Performance (EEP) indicator. The findings show that the use of renewable energy coupled with recycled materials provide highest efficiency performance in EEP (up to 260% higher than baseline). This combined approach facilitates upstream (material) and downstream (energy) activities, leading to substantially reduced emission and improved process value. The model is successful in developing and implementing sustainability strategies and tangible results by suggesting the applicability of the integration of LCA, LCC and OEE in manufacturing sectors in developing countries.

Limitations The analysis is limited to a single production line and is conducted with estimated rather than actual cost data. Future studies must transfer this method to a wide range of different fabrics and industries, integrate live operational data, and consider their inclusion in digital sustainability instrumentation (digital twins). In theory, this study contributes to the practice of circular economy evaluation at a micro-process level. From a practical perspective the EEP indicator provides a strong instrument which industry level decision makers can use as a tool to plan for sustainable production strategy. The methodology outlined in this paper has good potential for replication in other sectors engaged in low carbon, resource efficient industrial transformation process.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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