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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 remains a key strategic manufacturing industry contributing to economic development in many developing countries, including Indonesia. However, the sector's continued reliance on a linear take-make-dispose production model has driven substantial increases in energy consumption, carbon emissions, and solid waste, all of which impose adverse environmental consequences (Panagiotopoulou et al., 2022). The growing complexity of global supply chains, combined with heavy dependence on non-renewable natural resources, has made the transition toward a more sustainable economic model increasingly urgent (OECD, 2021), a concern reinforced by global policy commitments such as Sustainable Development Goal 12 on responsible consumption and production, particularly through the incorporation of renewable energy and reclaimed materials to reduce greenhouse gas emissions and water consumption in textile production (Schroeder et al., 2019). These environmental pressures translate directly into rising environmental costs, resource risks, and sustainability obligations that manufacturing firms must manage and report, positioning the issue squarely within the domain of environmental and sustainability accounting, and more specifically within environmental management accounting, the sub-field concerned with measuring and internalizing the economic consequences of environmental performance at the process level.

The circular economy has been widely proposed as the underlying conceptual and theoretical response to these sustainability pressures. Built on three core principles—the elimination of waste and pollution from the design stage, the circulation of products and materials to the maximum extent possible, and the regeneration of natural systems (Geng & Doberstein, 2008; Figge et al., 2023)—the paradigm reconfigures production from a linear to a closed-loop system in which waste and emissions are minimized while resource value is retained. For the textile sector specifically, this is operationalized through textile recycling, adoption of renewable fibers, eco-design for easier dismantling, and digital technologies that promote resource efficiency (Maware et al., 2022; Winkler, 2011), with indices such as Overall Circularity Effectiveness (OCE) proposed in the literature to capture the productivity, waste, and energy-efficiency dimensions of circularity (Castillo-Díaz et al., 2024; Baumer-Cardoso et al., 2023). Circular economy theory, however, does not by itself provide a mechanism for converting environmental and operational improvements into decision-relevant economic information; this role is instead assigned to environmental management accounting theory, which holds that environmental performance data must be translated into cost- and value-relevant information—through Life Cycle Assessment (LCA) for environmental impact, beginning with a Life Cycle Inventory of input-output data on energy, water, raw materials, and waste (Islam, et al., 2016; Zendoia, et al., 2014), and Life Cycle Costing (LCC) for economic performance—before it can support managerial decision-making, typically expressed as an eco-efficiency indicator relating economic output to environmental cost (Huppes & Ishikawa, 2005). This theoretical positioning needs critical extension, since existing applications of environmental management accounting have tended to operate at the level of disclosure or firm-wide reporting rather than at the level of specific manufacturing processes where circular-economy interventions are implemented.

Empirical LCA-based studies substantiate this theoretical framework across multiple textile processes. Fiber-material substitution studies show that renewable fibers such as hemp can reduce water use by 77% and energy consumption by 40% relative to conventional fabrics (Wiedemann et al., 2022), while cradle-to-gate assessments of organic-cotton shirt production report reductions in eutrophication of 96% and in global warming potential of 47% (Kazan et al., 2020). Recycling-oriented LCAs indicate that each kilogram of recycled fiber saves approximately 1.5 kg of CO2-equivalent emissions, 13 MJ of energy, and corresponding virgin-material inputs

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(Broadbent, et al., 2007). In contrast, process-level assessments of dyeing and finishing identify wet-processing stages as major sources of SO2 and NOx emissions (Shanbag & Manjare, 2020) and attribute up to 75% of total impact in thermally processed materials to thermal energy use (Ferreira, et al., 2016). System-level and gate-to-gate LCAs further demonstrate that energy-efficient equipment retrofitting can materially reduce process emissions and that solid-waste reuse offers potential as input for secondary products (Panagiotopoulou et al., 2022; Renzulli et al., 2016), and that circular product-design choices significantly affect environmental impact during the use and end-of-life phases (Delaney & Liu, 2023). This evidence is reinforced by Zero Defect Manufacturing research, which links system-wide reductions in production waste directly to improvements in eco-efficiency value (Psarommatis & May, 2023). Collectively, these findings confirm that LCA functions not merely as an environmental-impact reporting tool but as a basis for strategic decision-making, particularly when combined with economic dimensions such as Life Cycle Costing and eco-efficiency indicators to form a holistic sustainability evaluation system.

Nevertheless, despite this extensive body of LCA-based evidence, a limitation persists in developing simple yet comprehensive quantitative techniques that allow industry actors to evaluate circular-economy strategy options quickly and comparatively. Existing eco-efficiency indicators that integrate environmental impact assessment (LCA) with economic performance (LCC) can serve as a useful decision-support instrument at the level of manufacturing processes and systems (Delaney & Liu, 2023; Huppes & Ishikawa, 2005); however, such indicators have rarely incorporated operational effectiveness—captured through metrics such as Overall Equipment Effectiveness (OEE)—into a single, process-level measure, even though prior evidence shows that equipment- and energy-related interventions materially affect both environmental burden and operational efficiency (Panagiotopoulou, et al., 2022). This gap is the principal focus of the present study. The novelty of this research lies in the development of an Extended Eco-Efficiency Performance (EEP) framework that integrates environmental performance (EP), operational effectiveness (OEE), life-cycle cost (LCC), value performance (VP), and circular-economy implementation cost (COI) into extended eco-efficiency measures at both the process level (EEP) and the system level (EES), thereby extending environmental management accounting theory beyond conventional firm-level or disclosure-based applications toward an integrated decision-support instrument usable directly at the manufacturing-process level.

Based on this gap, this study aims to develop and apply an eco-efficiency assessment methodology to support the eco-friendly transformation of Indonesia's textile industry, using a medium-scale textile facility in West Java as the empirical setting and analyzing it through a gate-to-gate process boundary. The intended contribution is positioned within applied environmental management accounting: the proposed indicator translates environmental load, life-cycle cost, implementation cost, and equipment effectiveness into information that supports environmental cost recognition, green capital-budgeting decisions, internal sustainability reporting, and process-level management control. This positioning is consistent with prior accounting studies showing that green accounting and material-flow cost accounting can support sustainable development, while green accounting and sustainability disclosure are increasingly linked to firm value, financial performance, and sustainable finance decisions (Selpiyanti & Fakhroni, 2020; Faedah et al., 2025; Dwi RT et al., 2025). In doing so, the study offers accounting scholarship and practice a concrete, process-level measurement tool for evaluating the economic viability of circular-economy investments in manufacturing.

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2. METHODS

This research uses a single quantitative case-study design by developing an extended eco-efficiency indicator that integrates Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Overall Equipment Effectiveness (OEE). The design is appropriate because the research objective is to evaluate alternative circular-economy scenarios in one clearly bounded textile production setting rather than to generalize across firms statistically. The unit of analysis is a single cotton-fabric production line and its main process stages.

The facility and production line were selected purposively because they represent a medium-scale textile operation, use conventional energy and cotton inputs at baseline, and maintain process records needed for LCA, LCC, and OEE calculations. Process data include ideal cycle time, actual working time, daily output, defective and good output, energy consumption, and water usage. Environmental information, including emissions per process unit, was compiled using GaBi/LCA software and a gate-to-gate ISO 14044:2006 boundary. Cost data include energy costs, raw material costs, investment costs for new machinery, maintenance, and estimated downtime losses; all cost and performance values were normalized per production unit to enable scenario comparison.

Data verification was conducted by cross-checking production records, energy and water-use logs, and cost assumptions across the LCA, LCC, and OEE worksheets. LCC, OEE, VP, COI, EEP, and EES calculations were performed in spreadsheet-based calculation sheets, while GaBi was used for the LCA inventory and emission factors. To address uncertainty in estimated cost and emission data, a sensitivity check was added by varying the main cost, emission, and OEE inputs within a plausible range; the ranking of scenarios remained stable, with the combined scenario consistently producing the strongest system-level EEP.

$$CO_2 NO_x NH_3 \quad \textbf{(1)}$$

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

$$EP = \sum_{x=1}^{m} \frac{E_x . W_x}{N_x} \quad \textbf{(2)}$$

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.

$$E_x x W_x CO_2 = 1, NO_x = 298, SF_6 = 23900 N_x CO_2 \quad \textbf{(3)}$$

The third stage of the approach is LCC, where operational costs are assessed per process unit across 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 as follows:

$$OEE = A.P.Q \quad \textbf{(4)}$$

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

For clarity, the system-level indicator does not cancel VP from the numerator and denominator. EEP is computed at the process level as VP divided by the product of EP and COI, and EES is obtained by aggregating the validated EEP values across process units. This clarification corrects the previous algebraic ambiguity in Equation (11) and preserves the intended relationship among value creation, environmental burden, and implementation cost.

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

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 by substituting conventional cotton fibers with pre-consumer recycled cotton fibers generated from production waste. Scenario 3 is a combined strategy utilizing both

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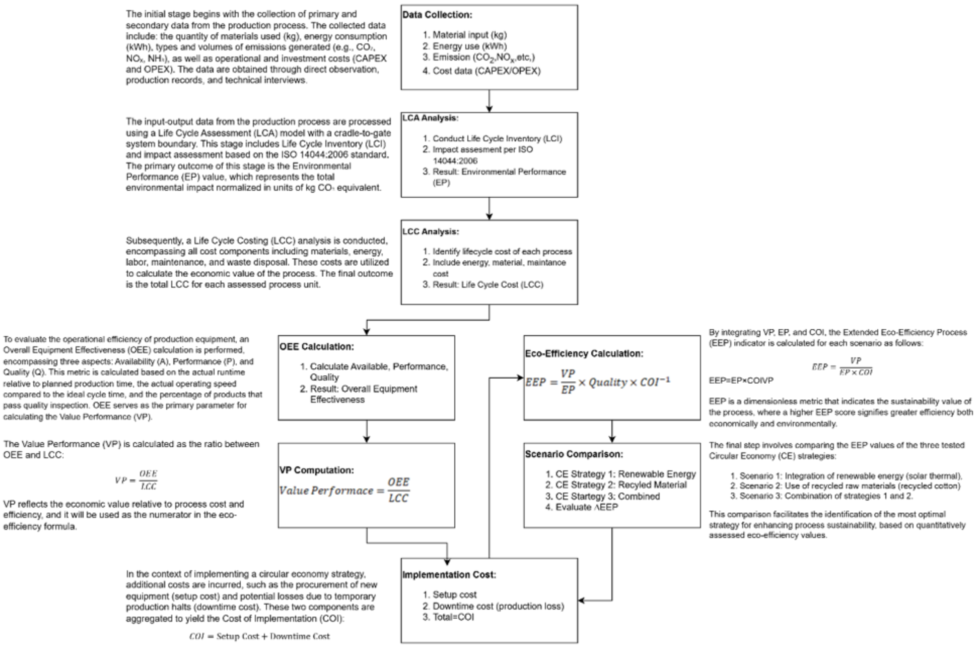
renewable energy and recycled materials simultaneously. The baseline scenario represents current operations without circular-economy intervention.



Source: Data Processing Results (2025)

Figure 1. Flow chart of Research Methodology.

The following diagram outlines the flow chart based on the procedures described above: inputs, processes, indicators, and scenario evaluation. The diagram shows that data flows from the beginning (technical & environmental data) through EP, VP, OEE, and COI analysis, and finally into eco-efficiency indicators. The evaluation was performed under four scenarios: baseline (without circular economy intervention), renewable energy use, recycled materials, and a combined strategy. The table and graph above present the values for each component, calculated using the methodology formulations.

3. RESULTS AND DISCUSSION

3.1 Environmental Impact (EP)

The carbon emissions level, in kg CO_2 eq/unit, indicates that the baseline scenario (without circular economy intervention) produces the highest environmental burden: 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 on conventional fibers, particularly primary cotton, which have a high carbon footprint in cultivation and initial processing. In addition, energy-intensive dyeing and finishing processes and extensive chemical use contribute to high emissions in the gate-to-gate phase of the product life cycle.

In the renewable energy scenario, emissions decrease by up to 3.8 kg CO_2 eq/unit, representing an environmental efficiency of almost 27% compared to the baseline. This decline mainly results from integrating alternative energy sources in the form of solar thermal systems, which replace most fossil electricity-based thermal energy needs. Although the raw material composition does not change, this strategy significantly affects the EP indicator, as the energy sector accounts for the largest share of the total carbon footprint in textile manufacturing. The study also supports the view that transitioning to clean energy sources is one of the most effective strategies for lowering emissions in 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 shows that using recycled fibers from production waste (pre-consumer recycled cotton) greatly reduces carbon emissions at the upstream end of the value chain. Replacing primary fibers with recycled fibers eliminates the need for cultivation, early processing (ginning, spinning), and inter-regional transport of raw materials, all major contributors to GWP. These findings are consistent with research showing that using organic and recycled fibers can reduce GWP by up to 47% and eutrophication by up to 96% (Kazan et al., 2020).

One of the most notable results comes from a combined scenario, with emissions reductions of up to 2.9 kg CO_2 eq/unit, equivalent to environmental efficiency gains of more than 44% compared to the baseline. Thus, combining these strategies creates a synergistic impact by reducing energy sources and raw materials in parallel, maximizing environmental efficiency across two sides of the life cycle. A consistent procedure lowers emissions from energy and material use, as well as 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. However, the effectiveness of this strategy depends on the point of intervention within the value chain—energy modifications significantly reduce direct energy consumption. In contrast, material changes strongly affect indirect emissions; combining the two strategies is suggested as the optimal approach 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 1**. The table presents results at the main process and system aggregate level, enabling an in-depth cross-strategy comparison.

Table 1. 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)	4.70E−05	4.70E−05	5.10E−05	5.36E−05
Eco-efficiency (EEP)				
1. Pre-treatment	8.0E−06	1.2E−05	1.3E−05	2.1E−05
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 1**, 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)

Value Performance (VP) is interpreted as the conversion of operational effectiveness into economic value by combining Overall Equipment Effectiveness (OEE) with Life Cycle Costing (LCC). The recycled-material scenario produced the highest stand-alone OEE because pre-consumer recycled cotton had more stable handling characteristics in the observed process, while the combined scenario produced the highest VP because lower material and energy costs compensated for transition costs at the system level.

Although the recycled-material scenario had the highest OEE, the combination scenario achieved the highest VP value (5.36×10^{-5}), calculated from OEE relative to total LCC. This indicates that the strongest process value is obtained when material substitution and energy efficiency are assessed together rather than as isolated interventions.

The renewable-energy scenario produced a VP value close to the baseline because the reduction in energy-related environmental burden was partly offset by transition costs and temporary operating adjustments. The slight decrease in OEE reflects the initial adaptation period for the new energy system, including technical tuning and production-capacity adjustment.

These results suggest that circular-economy interventions affect both environmental performance and management-accounting information. Energy and material choices change not only emissions but also unit costs, downtime costs, and the economic value generated by each process. The VP and EEP indicators therefore provide a basis for internal decision making, budgeting, and post-investment evaluation.

3.3 Cost Implementation (COI)

The Extended Eco-Efficiency Performance (EEP) indicator shows that the combined renewable-energy and recycled-material scenario achieved the strongest system-level result. Although this scenario has the highest implementation cost, the improvement in environmental performance and process value offsets the additional cost when assessed through the integrated EEP metric.

This case illustrates why environmental management accounting requires integrated information. A strategy with a higher initial investment may still be preferable when the reduction in emissions, resource use, and operating cost is converted into process-level value. The combined strategy reduces fossil-energy dependence and carbon-intensive primary feedstock use, which improves VP and increases EEP relative to single-intervention scenarios.

In contrast, the single-intervention scenarios on the energy and material sides produced lower EEP values than the combined scenario. This finding indicates that circular-economy effectiveness is not determined by investment size or emission reduction alone, but by the relationship among implementation cost, operational value, and environmental burden.

In this sense, the EEP indicator provides a practical evaluation context for green capital budgeting and internal sustainability control. Managers can use it to compare whether incremental spending on circular-economy implementation is justified by improvements in process value and reductions in environmental burden.

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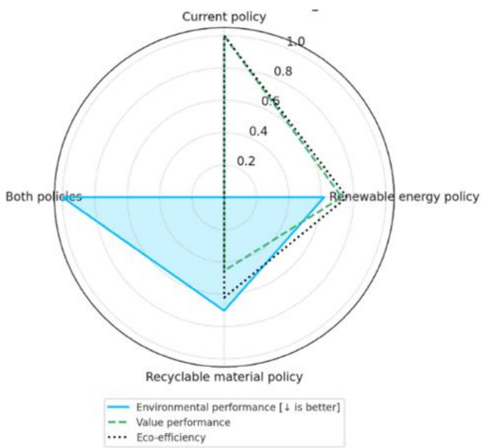
Table 2. Eco-efficiency (with COI)

	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+17	2.33E+12	2.25E+17
	EP change (%)	0.00	3.03	-0.51	6.57

Source: Data Processing Results (2025)

Table 2 presents a corrected COI-based eco-efficiency analysis for heating process 2. The table now separates raw scientific-notation values from normalized percentage interpretation to avoid the previous inconsistency. The combination scenario records the highest corrected eco-efficiency value (2.25E+17), and the accompanying percentage row is expressed as a normalized environmental-performance change rather than an unbounded raw percentage.



Source: Data Processing Results (2025)

Figure 2. Performance Comparison of CE Strategies in Heating Process 2 in Textile Manufacturing.

Figure 2 is a verified radar chart showing sustainability-indicator performance in heating process 2 as a key energy-intensive process. The revised figure caption removes the unverified AI-generated warning and the interpretation is limited to the indicators reported in **Table 2**.

3.4 Evaluation of Extended Eco-Efficiency (EEP) Indicators

The evaluation results demonstrate that the combined scenario has the highest system-level Extended Eco-Efficiency Performance (EEP), reaching 260% of the baseline index, or an improvement of approximately 160% over current operations. This correction aligns the discussion with Table 1 and avoids interpreting the index as only a 40% increase.

At a conceptual level, these results reinforce the argument that resource substitution and energy optimization can create a synergistic impact on production systems. In the integrated evaluation model, EEP tracks the relative contribution of EP, VP, and COI to system performance, providing a quantitative basis for management-accounting decisions such as investment prioritization, cost control, and sustainability-performance monitoring.

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EEP trends are reported as normalized scenario indices to support comparability across scenarios. The revised presentation avoids mixing raw EEP outputs with percentage values and shows moderate gains for single interventions and the strongest improvement for the combined strategy.

From a theoretical and practical perspective, the findings show that circular-economy investment can reduce environmental burden while improving process value when it is designed integratively. The expanded eco-efficiency indicator therefore operationalizes environmental management accounting at the process level by linking ecological impact, cost information, and operating effectiveness in one decision-support metric.

Table 3. Environmental performance by textile production process and circular-economy scenario

	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

Table 4. System-level value performance and extended eco-efficiency index by circular-economy scenario

System indicator	Current	Renewable	Recycled	Combination
Value performance (VP)	4.70E−05	4.70E−05	5.10E−05	5.36E−05
EEP index (Current = 100)	100	139	152	260

Source: Data Processing Results (2025)

Table 3 reports environmental performance (EP) for each textile production process under the current, renewable-energy, recycled-material, and combined scenarios. To avoid mixing detailed process values with system-level economic indicators, the VP and EEP summary is presented separately in **Table 4**. This separation makes the corrected numerical interpretation clearer and prevents mathematically implausible percentage readings.

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

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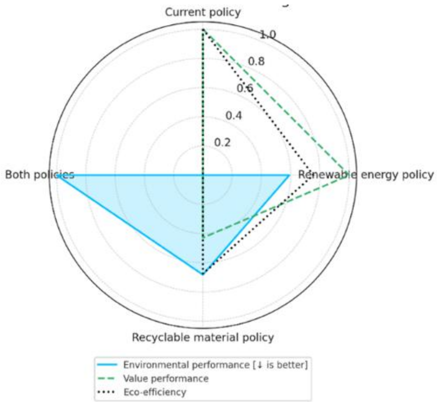
ability to represent cross-dimensional benefits in textile production systems as indicated by this visualization.



Source: Data Processing Results (2025)

Figure 3. Performance Illustration of Circular Economy Strategies

3.5 Practical and Theoretical Implications

In practical terms, this study contributes a data-based environmental management accounting model for circular-economy decisions in textile manufacturing. By integrating LCA, LCC, and OEE into the EEP indicator, managers can connect environmental costs, operating efficiency, and implementation expenditure in a single process-level measure. The model can support environmental cost recognition, green capital budgeting, internal sustainability reporting, and evaluation of whether circular-economy investments create sufficient operational value. Prior ASET evidence on green accounting, sustainability disclosure, and green finance supports the need for accounting tools that move beyond formal disclosure toward more substantive environmental-cost and investment information (Faedah et al., 2025; Dwi RT et al., 2025).

The simulation results show that changes in energy inputs, material substitution, downtime, and cost assumptions are reflected in the EEP value. A strategy that appears expensive at the investment stage, such as replacing the energy system, can be evaluated more fairly when its effects on emissions, resource cost, and process productivity are considered together.

Theoretically, the results extend environmental management accounting by showing how environmental and operational data can be converted into cost-relevant decision information at the micro-process level. The integration of LCA, LCC, and OEE addresses a gap in prior circular-economy studies that often report environmental improvement without connecting it to process-level cost behavior and managerial control. This also extends ASET's green-accounting discussion by offering a process-level measurement route that complements firm-level green accounting and material-flow cost accounting evidence (Selpiyanti & Fakhroni, 2020).

The framework can be adapted to other manufacturing settings when comparable technical, environmental, and cost parameters are available. However, its transferability depends on clearer documentation of case selection, data sources, software, and sensitivity procedures; these elements have been added to strengthen methodological transparency and replicability.

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4. CONCLUSION

This study assessed the effectiveness of circular-economy practices at the process level in textile manufacturing by integrating environmental, economic, and operational aspects through the Extended Eco-Efficiency Performance (EEP) indicator. The findings show that the combined use of renewable energy and recycled materials produces the strongest performance, reaching 260% of the baseline EEP index. The model demonstrates how LCA, LCC, and OEE can be translated into environmental management accounting information for evaluating green investment, process efficiency, and sustainability performance in manufacturing firms in developing-country contexts.

Limitations. The analysis is limited to a single production line in one medium-scale textile facility and therefore should be interpreted as an analytical case study rather than a general representation of the Indonesian textile industry. Cost data are partly estimated rather than fully audited actual costs, although sensitivity checks were added to test the stability of scenario rankings. Future studies should apply the framework to multiple firms, fabrics, and production technologies, use audited cost records and live operational data, and integrate the indicator into digital sustainability-control systems such as dashboards or digital twins.

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