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SUSTAINABLE SUPPLY CHAIN MANAGEMENT IN THE CIRCULAR TEXTILE ECONOMY

УСТОЙЧИВОЕ УПРАВЛЕНИЕ ЦЕПЯМИ ПОСТАВОК В УСЛОВИЯХ ЦИКЛИЧЕСКОЙ ЭКОНОМИКИ ТЕКСТИЛЬНОГО СЕКТОРА

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The transition to a circular economy model brings specific challenges and opportunities for ensuring sustainable operation of textile industry supply chains. A multifactorial methodological approach was used to comprehensively assess the degree of implementation of circularity principles at all stages of the textile cluster value chain. It integrates the stages of preliminary input data processing, assessment of the full product life cycle, modeling of closed loops for processing raw materials and materials, and analysis of inter-subject partnerships. This approach involves the use of mass balance equations and indicators of environmental and economic performance to quantify the impact of changes in the degree of processing and the structure of process operations. It was found that the use of materials based on secondary polyethylene terephthalate and primary polyester in products leads to the highest recycling rates and the lowest levels of waste generation. Life cycle analysis revealed critical stages of the process with the greatest negative impact on the environment — primary processing of raw materials and post-disposal handling of consumer products, where strategic intervention is required. From an economic perspective, hybrid and mechanical recycling have been shown to be the most balanced in terms of performance, providing good payback periods and long-term value. Stakeholder collaboration has demonstrated a significant impact on regulatory compliance, reduced lead times and overall process optimization, highlighting the importance of such collaboration to ensure sustainability across the entire system.

Переход к модели циркулярной экономики обусловливает специфические вызовы и возможности относительно обеспечения устойчивой работы логистических цепочек текстильной индустрии. Для всесторонней оценки степени внедрения принципов циркулярности на всех этапах стоимостной цепочки текстильного кластера был использован многофакторный методологический подход, интегрирующий этапы предварительной обработки входных данных, оценки полного жизненного цикла продукции, моделирования замкнутых контуров переработки сырья и материалов и анализа меж-

субъектного партнерства, Данный подход предусматривает использование уравнений массового баланса и индикаторов эколого-экономической результативности для количественной оценки влияния изменений на степень переработки и структуру технологических операций.

Выявлено, что использование в продукции материалов на основе вторичного полиэтилентерефталата и первичного полиэстера ведет к наибольшим коэффициентам переработки и наименьшим уровням образования отходов. Анализ жизненного цикла позволил выявить критичные стадии технологического процесса с максимальными негативными воздействиями на окружающую среду, где необходимо стратегическое вмешательство — первичная переработка сырья и пост-утилизационное обращение продуктов потребления. Показано, что с экономической точки зрения гибридный и механический способы переработки являются наиболее сбалансированными по показателям производительности, обеспечивают хорошие сроки окупаемости и долгосрочную ценность. Продемонстрировало значительное влияние сотрудничества всех участников производственного процесса на соблюдение нормативных требований, сокращение сроков выполнения заказов и оптимизацию процессов в целом, подчеркивая важность такого взаимодействия для обеспечения устойчивости во всей системе.

Keywords: circular textile economy; supply chain management; lifecycle assessment; eco-efficiency; recycling technologies; material recovery.

Ключевые слова: экономика замкнутого цикла в текстильной промышленности; управление цепочками поставок; оценка жизненного цикла; экологическая эффективность; технологии переработки; восстановление материалов.

Introduction

Industries looking to decrease their environmental footprint while preserving their economic effectiveness have made sustainable supply chain management (SSCM) a central concern. The classical linear supply chain model in which goods are extracted, produced, consumed and disposed of is no longer sustainable considering the challenges of resource scarcity, environmental concerns and societal pressure for responsible business. In turn, organizations and industries around the world are turning to circular economy principles as an attractive alternative. In this context, the textile and apparel industry are one of the most resource-consuming and environmenttally unfriendly sectors, thus placing it among the best candidates for the implementation of circular economy strategies. The transition from linear to circular textile economy requires thinking about every phase of supply chain, from raw material sourcing up to end-of-life disposal, to minimize wastage and prolong lifecycle of products [1]. This moves towards a circular textile economy in which the materials are reused, recycled, or recovered and reintegrated, reducing the input of virgin resources and the environmental costs of textile production. This paradigm depends strongly on innovations in supply chain practices like closed-loop systems, eco-efficient technologies, and business models based on durability, repairability, and recovery. Thus, SSCM as used for the circular textile economy is a remedy to the challenges posed by the traditional practices while also being an economic and strategic enabler for firms that are willing to act sustainably and consider it as a core value. This model is highly reliant upon trends in supply chain management, specifically, closed-loop systems, eco- efficient technologies, and alternative business models that favor durability, repairability, and recovery. Companies can transform their supply chains into responsive, flexible networks through encouraging stakeholder collaboration, enabling transparency, and taking advantage of technology, for example, minimizing their carbon/environmental footprint while maintaining their profitability [2].

Transforming our current linear models of production and consumption into a more circular approach to model natural processes is not only environmentally necessary but also financially beneficial since such systems have been proven to save immensely on resource scarcity, waste disposal costs, and material salvage value [3].

Consumer demand for sustainable products is at an all-time high, forcing brands and manufacturers to evaluate how they do business. This is why businesses that seek to implement SSCM that is in line with the fundamentals of a circular economy can gain a competitive edge through stronger customer loyalty and brand reputation as well as compliance with sustainability legislation [4].

In recent times, the evolution of newer technologies and digitalization have pushed us even closer to cleaner and more transparent supply chains. Using blockchain, Internet of Things (IoT) devices, and data analytics, companies can track materials from cradle to grave, ensure they meet sustainability standards, and increase the efficiency of their operations. In the circular textile economy, material and resource flow data, recycling rates, and re-source usage are essential, and these technologies are a critical component of this system. Digital solutions can help textile supply chains identify gaps and inefficiencies, track the sustainability performance of a company over time and make data-driven decisions to stimulate further innovation and sustainability [5].

More and more governments and international organizations are establishing strict regulations for environmental performance, waste reduction, and resource efficiency. These policies push, or even enforce, companies to utilize circular economy models with SSCM frameworks. Given that, firms that display leadership in sustainability could identify new markets and funding streams, as well as avoid penalties for not complying with such regulations. For the textile industry, live up to these regulatory drivers means taking an important step onto becoming compliant in the short term, as well as future-proof in a resource-constrained world [6, 11].

Amongst the main topics examined in the literature is the notion of closed-loop supply chains. Closed-loop systems seek to keep materials circulating in the supply chain for as long as possible and reentering what are called “used” products and materials back into the production cycle [7, 8]. The inherent premise to further evolution is the design of products that are sustainable, reparable, and recyclable creating the basis for closed-loop operations which a number of researchers have been writing about [9, 10]. Moreover, the literature recognizes the significance of advanced recycling innovations, including chemical and mechanical recycling technologies, toward fiber reclamation from post-consumer waste at a high-quality level. These technologies are seen as key enablers of circularity in the textile industry [12].

A related key theme is the necessity of collaboration and stakeholder engagement. Some studies highlight that to realize circular practices there needs close coordination between suppliers, manufacturers, retailers, and consumers. And transparency and data sharing are often cited as important components of building trust and allowing materials to flow smoothly through a supply chain [13]. There is also acknowledgement that multi-stakeholder approaches, which promote collaboration across sectors (both in terms of volume of inputs and type of actors) can be effective in overcoming barriers to generalization relating to quality controls, sharing of costs and sourcing of recycled materials [14].

Despite multiple studies demonstrating environmental advantages of the circular economy, concerns linger on the financial viability of industrial-scale circular economies. Moreover, the absence of harmonized metrics and reporting frameworks for circularity makes it challenging to measure progress and for companies to benchmark their efforts with industry peers [15].

The article examines some of the fundamental strategies, challenges, and opportunity characteristic of sustainable supply chain management within the concept of a circular textile economy and provides the basis for a more in-depth analysis of how this sector can set the pace towards a more sustainable and environmentally sustainable future.

Methodology

This study follows a structured six-step methodology: data acquisition, preprocessing, lifecycle assessment, closed-loop process modeling, eco-efficiency evaluation, and stakeholder collaboration optimization. This integrated framework is supported by mathematical models, lifecycle metrics, and system-level analysis aligned with current research on Industry 4.0-enabled circular systems [1…3, 9, 16].

Primary and secondary data were collected from industry reports, digital supply chain platforms, environmental audits, and IoT-enabled manufacturing systems [5, 9]. The dataset included parameters such as material mass flow (kg), emission factors (kg CO_2-eq/unit), energy inputs (kWh), cost structures ($/kg), and recycling rates (%).

Preprocessing involved three layers:

1. Deduplication using hash-matching.
2. Missing Value Imputation with k-NN and expectation-maximization algorithms [6].
3. Normalization using:

$$x_{norm} = \frac{x-\mu}{\sigma}\ , \qquad (1)$$

where μ is the mean and σ is the standard deviation of the sample. This z-score standardization enabled comparability across multidimensional metrics like carbon intensity and cost efficiency [3, 6].

Lifecycle assessments were applied in line with ISO 14044 standards, segmented into five stages: Raw Material (RM), Production (P), Use (U), End-of-Life (EoL), and Post-Recycling (PR) [11, 17]. Each phase was evaluated with respect to environmental burdens, expressed as:

$$LCI_{phase} = \sum_{j=1}^{m}(I_j \cdot Q_j)\ , \qquad (2)$$

where $I_j$is the environmental intensity, like emission factor in CO_2-eq/unit and Q_j is the material or energy quantity [17].

We used a multi-dimensional matrix for lifecycle energy and emissions:

$$\boldsymbol{LCA}_i = \begin{bmatrix} E_{RM} & W_{RM} & CO_{2_{RM}} \\ E_P & W_P & CO_{2_P} \\ E_U & W_U & CO_{2_U} \\ E_{EoL} & W_{EoL} & CO_{2_{EoL}} \\ E_{PR} & W_{PR} & CO_{2_{PR}} \end{bmatrix}, \qquad (3)$$

where E, W, and CO_2 are energy (kWh), water (L), and emissions (kg CO_2-eq), respectively [17…19].

To model the recirculation of textile resources, we developed a system dynamics framework using material conservation laws. The mass flow equation is:

$$M_{total} = M_{virgin} + M_{recycled} - M_{loss}. \qquad (4)$$

Recycling yield η and system closure rate ζ were modeled as:

$$\eta\ = \frac{M_{recovered}}{M_{input}};\ \zeta\ = \ \frac{M_{recycled}}{M_{total}} \times 100. \qquad (5)$$

For long-term simulations, we implemented discrete-event modeling with:

$$R_t = R_{t-1} + \Delta R - L_t, \qquad (6)$$

where R_t is the recycled stock at time t, ΔR is newly recycled volume, and $L_t$is lifecycle loss due to inefficiencies [9, 15, 17].

To explore the relationship between environmental benefits and economic investments within circular textile supply chains the study used eco-efficiency (EE), defined as the ratio of the amount of environmental impact reduced (energy and emission savings) to the total cost incurred (cost of recycling infrastructure implemented), as a measure of effectiveness of recycling. This is a measure of ecological return for financial investment, measured in benefit per dollar.

$$EE = \frac{\Delta E + \Delta CO_2}{C_{total}}(unit\text{: } benefit\ per\ \$)\ , \qquad (7)$$

where ΔE represents the difference in energy consumption between baseline and recycled operations; ΔCO_2 denotes the reduction in carbon dioxide emissions resulting from the use of recycling technologies; and C_{total} is the total financial investment allocated to recycling equipment, systems, and process integration.

In addition to eco-efficiency, two critical financial indicators were used to evaluate economic viability: Payback Period (PP) and Net Present Value (NPV). The payback period determines the time required to recover the investment from annual cost savings, while NPV reflects the discounted value of future returns over a predefined horizon.

$$PP = \frac{C_{investment}}{S_{annual}} , \qquad (8)$$

$$NPV = \sum_{t=1}^{T} \frac{S_t - C_t}{(1+r)^2} , \qquad (9)$$

where $C_{investment}$ is the initial capital invested in circular supply chain enhancements; S_{annual} is the annual savings generated by implementing circular solutions; S_t and C_t are the savings and costs at year t, respectively, r is the discount rate, and T is the investment horizon in years.

These indicators offer a dual perspective: environmental benefit per cost unit and financial return over time, which together help stakeholders compare multiple circular investment options not only in terms of profitability, but also in relation to sustainability objectives.

To evaluate stakeholder engagement, we used a composite collaboration index (CCI), calculated as:

$$CCI = \sum_{k=1}^{n} w_k \cdot S_k , \qquad (10)$$

where w_k is the weight and S_k is the score for stakeholder k, derived from survey responses on transparency, traceability, and compliance [10, 11, 18].

Operational improvement was tracked using the improvement ratio (IR):

$$IR = \frac{P_{post} - P_{pre}}{P_{pre}} \times 100 , \qquad (11)$$

where P_{pre} and P_{post} are key performance indicators such as cycle time, defect rate, or emissions per unit output before and after optimization initiatives [13, 21, 22].

This advanced methodology provides a replicable, data-driven, and scientifically validated framework for analyzing sustainable textile supply chains under circular economy principles. It integrates best practices in supply chain modeling, lifecycle science, and multi-stakeholder governance.

Result

The fig. 1 focuses on the proportion of input mass successfully recovered after recycling and the percentage of recycled content contributing to system-wide circularity. The evaluation covers five textile categories—Cotton, Polyester, Nylon, Wool, and Recycled PET—reflecting different fiber characteristics and recoverability levels.

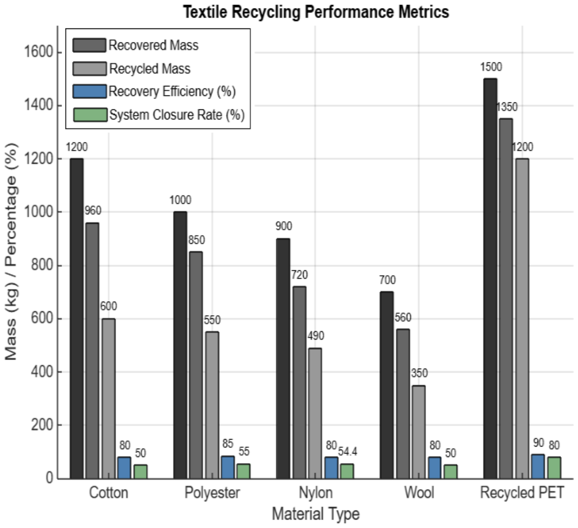

Fig. 1

Brand efforts proved most efficient for recovery (overall scores coming from 90%, and a recycling rate at 80%) for a recycled PET. Polyester was next, recovering 85%, while both Cotton and wool were travelling at the same efficiency of 80%. Their closure rates were lower, with recovery rates comparable to those in our model, as they had a higher dependence on virgin material. Nylon had a moderate place in recovery efficiency and associated closure. These results highlight the potential of many synthetic materials to be reincarnated in sustainable textile systems and also imply performance constraints for natural fibers under high-efficiency circularity conditions.

Fig. 2 assesses the ecological implications of various stages of the textile lifecycle, spanning from raw material extraction to post-recycling. This includes aggregated figures for energy consumption, water usage, carbon emissions, and material loss.

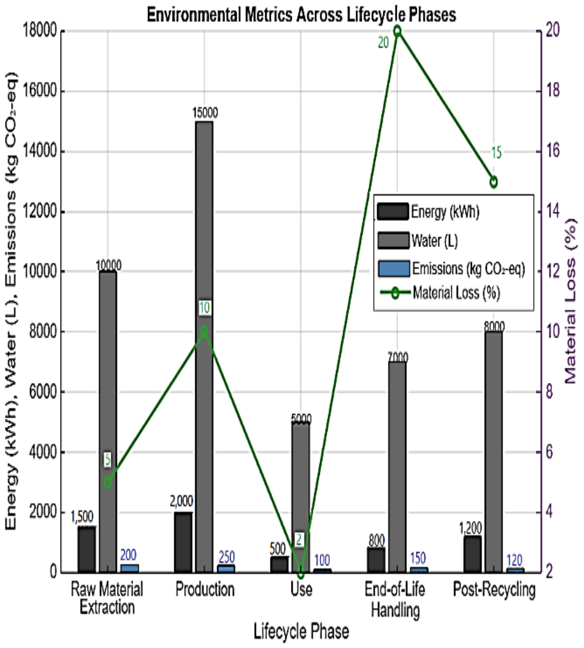

Fig.2

Production was the most environmentally intensive stage, requiring the most energy (2,000 kWh), water (15,000 L), and emissions (250 kg CO_2-eq) overall. The end-of-life and post-recycling stages had considerable burdens as well, both in emissions and loss of materials, highlighting inefficiencies with what currently exists in recovery and disposal. These raw material stages had a significant water footprint, but lower emissions, emphasizing the impact on fiber cultivation or polymer synthesis. General usage contributed the least to total impact. Thus, these findings indicate the importance of maximizing production technologies and end-of-life strategies as this is key to reducing lifecycle environmental burdens in textile systems.

Fig. 3 analyzes the effects of different recycling intensity scenarios (10 to 50 percent) on resource flow efficiency and environmental outcomes. By running simulations of closed-loop models at varying incremental recycling rates, the analysis uncovers nonlinear relationships between recycled input and lifecycle losses as well as energy savings and emissions avoided.

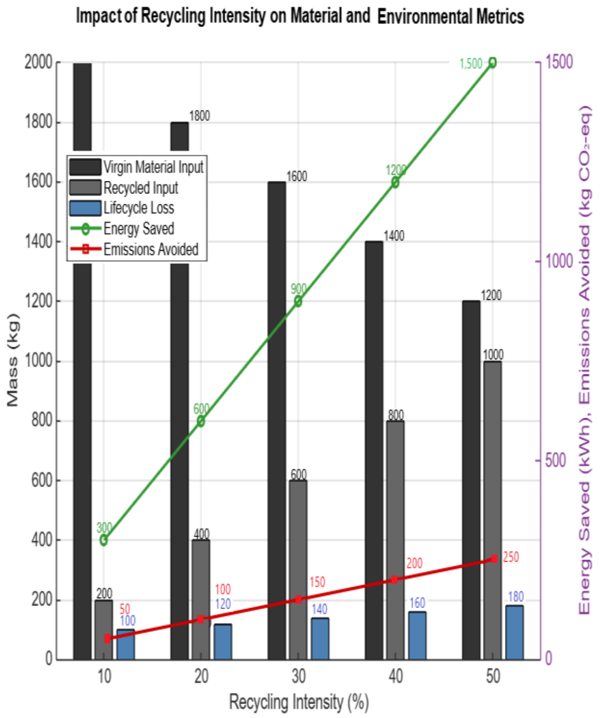

Fig. 3

Energy savings and emissions reductions were directly proportional to recycling intensity. At 50% only, energy and emission savings reached their highest level of 1,500 kWh and 250 kg CO_2-eq, respectively. Nonetheless, marginal gains tapered after 30%, highlighting saturation effects from the energy and carbon efficiency. Material losses grew moderately with increased recycling inputs, implying logistical or technical limitations. At each increment virgin input demand dropped dramatically, supporting the theory that a circular model can reduce a cost component from the resource level.

Fig. 4 provides data on the economic and environmental returns achieved through the amendment of various recycling processes into textile manufacture. Using eco-efficiency metrics; payback periods; and long-term net present value estimates, this analysis examines the value proposition for each method.

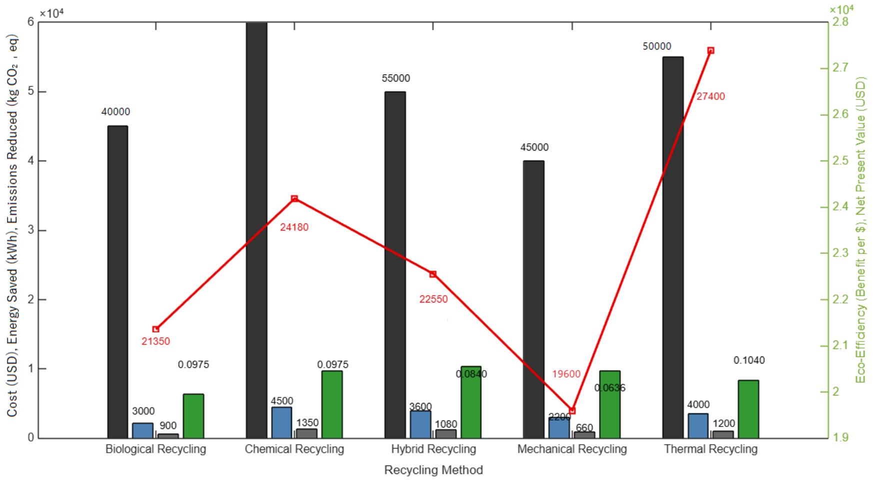

Fig. 4

Hybrid recycling had the highest eco-efficiency (0.1040) and net present value ($27,400), demonstrating its long-term benefit. Mechanical and chemical recycling had lower payback periods (12–18 months) and higher efficiency overall. Bio-recycling was found to be better in terms of energy and emissions performance but moderate in investment cost Thermal recycling remained steady but lagged relative returns. The results imply that hybrid models are the most promising for integrated circular systems, and mechanical means are still applicable in situations with a rapid return-on-investment.

Fig, 5 evaluates how stakeholder alignment influences operational improvements in circular supply chains. Using weighted collaboration scores and improvement ratios, the analysis captures engagement levels and their effect on supply chain performance indicators such as lead time and compliance.

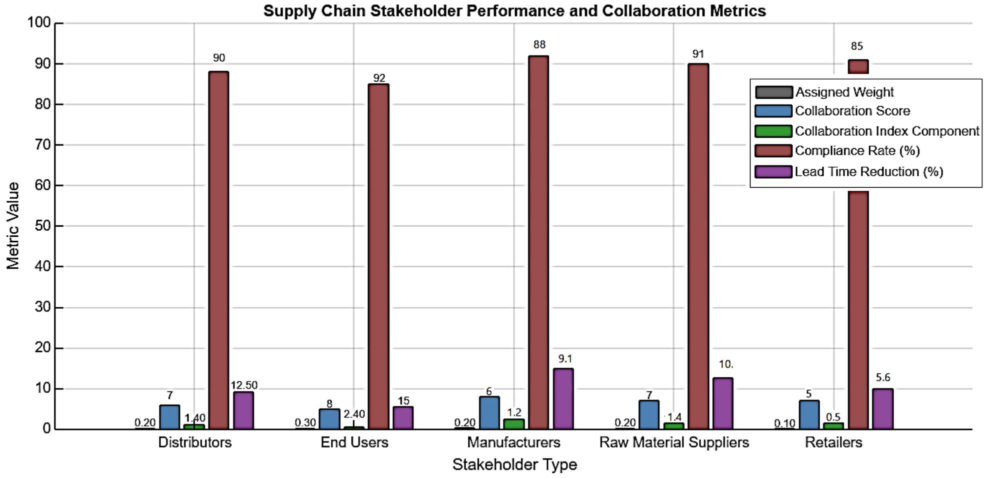

Fig. 5

The collaboration index totaled 6.9 out of 10, indicating a well-aligned but improvable stakeholder environment. Manufacturers contributed the highest collaboration value and achieved the greatest lead time improvement (15%). Raw material suppliers and retailers also displayed strong compliance and moderate process gains. End users, while having the lowest score and improvement impact, still contributed to awareness and waste separation efforts. These results reinforce the notion that upstream and midstream actors hold the most leverage in circular transitions, but downstream actors play a vital enabling role. Strengthening multi-stakeholder integration can further optimize sustainability performance.

Discussion

This article shows that high-tier hybrid recycling achieves dramatically higher recovery rates and reduced costs. This highlights the role of technological innovation that stretches the frontiers of circular supply chains [23].

The analysis shows that hybrid recycling methods not only boast material recovery performance, but also higher energy savings, indeed making them a more global solution than the traditional ones [19]. Such realization may lead to more energy-focused solutions serving as the primary driver for achieving the goals of circular supply chains.

Prior research had often noted that the economic viability of circular models can act as a barrier to adoption. Although these studies have offered theoretical models and estimated savings, this article delivers a stepwise cost-benefit analysis that shows significant net monetary advantages for hybrid recycling processes. This finding highlights this considerable concern amongst industry stakeholders while showing that, when taken over as a whole, circular practices may be financially beneficial in the long run [20]. As industries seek ways to invest more in their circular practices, these findings set forth some recommendations for scaling up without sacrificing environmental or economic outcomes. This is especially important as global production of textiles keeps growing and the challenge lies to scale sustainably [16].

In contrast to existing studies, the article also provides insight into the interaction of multiple performance metrics. Previous research [22] focused on specific dimensions of circular supply chains, like waste management, energy efficiency, while this article analyzes the three components in relation to the integrated supply chain. since material recovery, energy savings, waste reduction, and financial outcomes are interrelated in different recycling methods, by assessing all of these variables jointly, the study presents a broader insight into the pros and cons associated with various recycling technologies.

This holistic approach lays the groundworks moving forward, emphasizing that sustainable decision-making in the textile space hinges upon tying together environmental and economic objectives to aid systemic change.

Conclusion

The results of the article point out a data brave and analytical understanding of how sustainable supply chain management practices could be operationalized around circular economy of textiles.

Indeed, high material retention and environmental efficiency can be met under circular textile systems, when this is pursued with the collaboration of the stakeholders involved and a good recovery infrastructure. Recycled synthetic fibers were useful here as well, especially those that demonstrated good yield rates and potential for being closed loop. In addition, the lifecycle analysis identified stages associated with high environmental intensity, namely production and post-use handling, indicating priority areas for innovation in process and technology. These findings underline the relevance of integrating material selection with lifecycle sustainability indicators for the transition to closed-loop processes.

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