INTEGRATING CIRCULAR ECONOMY IN TO SUSTAINABLE DEVELOPMENT GOALS: INSIGHTS FROM LIFE CYCLE IMPACT ASSESSMENT

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Milena Rajic
Assistant Professor, University of Nis Faculty of Mechanical Engineering, Street: Aleksandra Medvedeva 14, Nis, Serbia
milena.rajic@masfak.ni.ac.rs

Zorana Stanković
Assistant Professor, University of Nis Faculty of Mechanical Engineering, Street: Aleksandra Medvedeva 14, Nis, Serbia
zorana.stankovic@masfak.ni.ac.rs

Peđa Milosavljević
Full Professor, University of Nis Faculty of Mechanical Engineering, Street: Aleksandra Medvedeva 14, Nis, Serbia
pedja.milosavljevic@masfak.ni.ac.rs

Vesna Jovanović
Associate Professor, University of Nis Faculty of Mechanical Engineering, Street: Aleksandra Medvedeva 14, Nis, Serbia
vesna.jovanovic@masfak.ni.ac.rs

Abstract

The integration of the circular economy into sustainable development goals offers an approach to sustainable resource management and economic growth, with Life Cycle Impact Assessment (LCIA) as a tool for evaluating environmental and socio-economic outcomes. This study investigates how LCIA methodologies can drive circular economy strategies within the textile industry, addressing sustainable development goals and targets such as responsible production and consumption and climate action. Textile production, which accounts for approximately 10% of global carbon emissions and 20% of industrial water pollution, presents significant opportunities for circular economy practices like recycling, reusing, and material innovation. Case studies from European textile manufacturers demonstrate the potential of LCIA in optimizing resource use, minimizing waste, and reducing greenhouse gas emissions by up to 50% when transitioning from virgin polyester production to closed-loop recycling systems. LCIA software tools such as OpenLCA and GaBi were employed to assess the environmental impacts across lifecycle stages, including raw material extraction, manufacturing, distribution, and end-of-life disposal. Results indicate that incorporating recycled fibers can lower energy consumption by 30–40%, while water usage can be reduced by as much as 70% compared to conventional production methods. Furthermore, the adoption of eco-design principles, supported by LCIA insights, showed a potential reduction in landfill waste by 25% through product lifecycle extension initiatives such as repair and reuse programs. This research highlights the socio-economic implications of circular economy adoption, including job creation in recycling and upcycling sectors, which could increase by 15% in regions implementing waste management systems. Policy recommendations emphasize the importance of regulatory frameworks that incentivize sustainable practices, such as extended producer responsibility and subsidies for green technologies. The findings show the value of cross-sector collaboration, combining insights *from LCIA with circular economy strategies to improve sustainable consumption patterns and support the transition towards a low-carbon textile industry.*

Key words: *circular economy, life cycle impact assessment, resource management, recycling and reuse*

Introduction

The global textile industry is one of the most resource-intensive and environmentally damaging sectors, contributing to 10% of global carbon emissions and 20% of industrial water pollution (Ellen MacArthur Foundation, 2019). As concerns over environmental sustainability intensify, circular economy principles have gained momentum as a transformative approach to addressing the industry's environmental and socio-economic challenges. The circular economy promotes closed-loop systems that minimize resource extraction, optimize waste recovery, and extend product lifecycles. In the textile sector, this translates into strategies such as fiber-to-fiber recycling, eco-design, and sustainable material innovation. However, effectively integrating these principles into industry practices requires quantitative assessment methodologies to evaluate their environmental and economic benefits. This is where the Life Cycle Impact Assessment is most commonly used. LCIA represents an analytical tool used to quantify the environmental impacts of a product or process across its entire lifecycle, from raw material extraction and manufacturing to use and end-of-life disposal. With LCIA, industries can identify environmental hotspots, optimize resource efficiency, and compare the sustainability performance of different circular economy strategies. Despite the increasing relevance of LCIA, its integration with CE strategies within the textile industry remains underexplored, particularly in the context of achieving sustainable development goals. This paper aims to bridge this gap by analyzing the role of LCIA in driving circular economy transitions within the textile industry. By focusing on sustainable development goals targets such as responsible production and consumption (SDG 12), climate action (SDG 13), and sustainable industry innovation (SDG 9), this study analysis how LCIA methodologies can improve decision-making for sustainable textile production (Hales & Birdthistle, 2022), (Küfeoğlu, 2022). The United Nations Sustainable Development Goals (SDGs) provide a global framework for sustainable economic, social, and environmental progress. The textile and apparel industry, valued at approximately $2.4 trillion, is a driver of economic growth and employment, yet it remains one of the largest contributors to pollution, carbon emissions, and resource depletion (UNEP, 2022). The integration of circular economy principles within the textile industry aligns directly with sustainable development goals, specifically: (1) SDG 12 - Responsible consumption and production, meaning reducing textile waste through recycling, reusing, and material recovery; (2) SDG 13 - Climate action, meaning that lowering carbon emissions through LCIA-informed eco-design and closed-loop production systems; (3) SDG 9 - Industry, innovation, and infrastructure, meaning encouraging sustainable industrialization through innovations in textile recycling technologies. However, the successful implementation of circular economy strategies requires a scientific, data-driven approach that goes beyond theoretical sustainability goals. LCIA enables a systematic evaluation of environmental trade-offs, ensuring that CE transitions lead to measurable sustainability benefits rather than unintended environmental consequences. LCIA provides quantitative insights into the sustainability impacts of different production methods, material choices, and waste management strategies. LCIA pinpoints high-impact processes within the textile lifecycle, such as dyeing (responsible for 20% of global industrial water pollution) and polyester production (generating 1.5 kg CO_2e/kg of fabric). It enables industry stakeholders to prioritize mitigation strategies, such as adopting waterless dyeing techniques or shifting to recycled polyester. Conventional textile production follows a linear “take-make-waste” model, where raw materials are extracted, processed, and discarded. But on the other hand, LCIA allows for the comparison of linear and circular production models, demonstrating how closed-loop systems reduce carbon footprints by 40-60% and cut energy use by 30-50% (Hammar, Peñaloza, Hanning, 2024), (Lozano-Oviedo, Cortés, Rey, 2024). LCIA determines the most sustainable textile materials by assessing factors such as energy intensity, water use, and recyclability. LCIA studies show that mechanically recycled polyester emits 50% less CO_2 than virgin polyester while organic cotton consumes 91% less water than conventional cotton (Periyasamy, Militky, 2019), (Kamble, Behera, 2021).

The objectives of this paper are to analyze how LCIA methodologies influence circular textile decision-making and to quantify the environmental benefits of circular economy textile strategies using LCIA data.

Literature Review

LCIA evaluates environmental impacts associated with all stages of a product's life cycle, from raw material extraction to disposal. In textiles, LCIA identifies environmental hotspots and informs sustainable practices. A systematic review (Bianco, et al., 2023) analyses studies on LCIA applications in textiles, revealing that the production phase, particularly raw material extraction and manufacturing, contributes significantly to environmental impacts. Cotton cultivation accounts for approximately 90% of water consumption in the life cycle of cotton garments. Additionally, the dyeing and finishing processes are responsible for about 20% of industrial water pollution globally. The paper (Bicalho, et al., 2017) compared LCIA methodologies, highlighting discrepancies in data quality and system boundaries. It found that using site-specific data reduced uncertainty by approximately 10% compared to generic datasets. This shows the importance of accurate data collection in LCIA studies to improve reliability.

The circular economy model aims to minimize waste and maximize resource efficiency by creating closed-loop systems. In the textile industry, circular economy frameworks have been adopted to address sustainability challenges. The review (Ramírez-Escamilla, et al., 2024) analyzed articles on circular economy strategies in the textile sector, identifying reuse, recycling, repair, and reduction as primary strategies. The study emphasized that implementing these strategies could reduce greenhouse gas emissions by up to 30% and decrease water consumption by approximately 50% (Ramírez-Escamilla, et al., 2024). Moreover, the paper (Furferi, Volpe, Mantellassi, 2022) proposed guidelines for textile industries transitioning to circular economy practices, for efficient use of natural resources, adoption of renewable energies, waste reduction, and effective end-of-life product management. Implementing these guidelines could lead to a 20% reduction in production costs and a 25% decrease in environmental impact.

The paper (Edirisinghe, de Alwis, Wijayasundara, 2024) highlights that the textile sector is responsible for 8-10% of global greenhouse gas emissions and 20% of worldwide wastewater pollution. The authors analysed that the most significant environmental impacts occur during the fiber production and wet processing stages. For instance, cotton cultivation in countries like India and Turkey is associated with high water use, pesticide pollution, and soil degradation, scoring up to 10 in environmental significance. Wet processing, particularly dyeing and finishing, is water-intensive and contributes substantially to chemical pollution and energy consumption. Lifecycle thinking and hotspot mapping revealed stages, such as raw material extraction, fabric dyeing, and end-of-life disposal, where circular economy strategies like water recycling, renewable energy adoption, and sustainable farming can be most effective. The paper's qualitative methodology, based on expert input from professionals and guided by UNEP's 2021 Eco-I Manual, offers a practical, low-cost alternative to conventional LCA software for identifying hotspots and proposing targeted circularity interventions across the product lifecycle.

It is important to emphasize that the textile and clothing industry is among the five most polluting and resource-intensive sectors globally, contributing significantly to water pollution and greenhouse gas emissions. While the concept of the circular economy offers a promising alternative to the traditional linear model, its practical implementation remains limited. The paper (Salmi & Kaipia, 2022) found that incumbent textile firms face path dependencies due to legacy product portfolios, product-oriented business cultures, and limited control over supply chains. In their case study of seven Finnish companies, only one was classified as a "circular incumbent," while others struggled to shift from selling low-cost, short-lived fashion items to service-based or recycled offerings. For example, a company specializing in affordably admitted that its product prices were too low to make rental models viable. Conversely, "born circular" companies successfully used waste materials like safety belts and cutting scraps to drive sustainable design. The paper highlights the importance of dynamic capabilities, such as sensing regulatory shifts, seizing design opportunities, and transforming supply chains, for enabling this transition. It emphasizes that firms with strong internal control and RFID-enabled tracking of garments were better positioned to implement circular business models and reduce waste through repair and reuse strategies.

Applying LCIA methodologies and circular economy frameworks is important for the textile industry, given its substantial environmental footprint. Textile production is responsible for about 20% of global clean water pollution from dyeing and finishing products.

Implementing zero-waste fashion strategies, such as zero-waste pattern design, can significantly reduce the average 15% textile waste generated during standard garment production. Furthermore, adopting circular fashion models, which emphasize designing for longevity, using sustainable materials, and promoting recycling, can contribute to a more sustainable and resilient textile industry.

Analysis of case studies

The following detailed analyses of case studies provide insights into the environmental footprints of different textile products. Bianco et al. (2023) conducted a cradle-to-gate LCA of a woollen undershirt produced in Italy, aiming to identify environmental hotspots in its production process. The study revealed that the total global warming potential of one undershirt is 11.7 kg CO_2e, with the sheep farming phase contributing 88% of these emissions. Energy consumption during the wool transformation process accounted for 11% of the total emissions, partially mitigated by the use of electricity from photovoltaic panels. Materials such as chemicals and transportation had negligible contributions to the overall environmental impact. The paper highlighted that user habits influence the environmental impact during the use phase of the undershirt.

Cotton Incorporated conducted a comprehensive LCA to evaluate the environmental impacts of cotton fiber and fabric production, covering stages from cultivation to finishing. The study found that producing 1,000 kg of woven cotton fabric requires approximately 8,000 cubic meters of water, with irrigation during cultivation being the primary contributor. The total energy consumption for producing the same amount of fabric was found to be significant, with notable contributions from both agricultural and textile processing stages. These findings underscore the importance of focusing on the cultivation stage to reduce water and energy consumption in cotton textile production (Barnes, et al., 2010).

The paper (Sandin et al., 2024) evaluated the environmental impacts of a garment made from chemically recycled fibers, considering stages from raw material extraction to end-of-life. The study demonstrated that using chemically recycled fibers resulted in a 60% reduction in energy consumption compared to virgin polyester production. Additionally, there was a 50% decrease in global warming potential, equating to a reduction of 2.5 kg CO_2e per garment. Water usage was also reduced by 70%, saving approximately 150 liters per garment. This case study highlights the environmental benefits of incorporating recycled materials into textile production.

Digital tools used for LCA analysis in the textile industry

LCA software tools are important for evaluating the environmental impacts of products within the textile industry. A comparative analysis of LCA software tools shows the features, strengths, and limitations of this sector (Table 1). SimaPro is the most frequently used LCA software in textile-related environmental assessments. In textile LCAs conducted with SimaPro, a wide range of system boundaries were applied, most notably cradle-to-gate and cradle-to-grave, enabling evaluations from raw material extraction to end-of-life stages. SimaPro supported assessments with standardized units (e.g., kg CO_2e/kg of material), allowing direct comparisons. For example, in the paper (Fonseca et al., 2023) wool yarn production evaluated using SimaPro revealed a remarkably high global warming potential of 95.70 kg CO_2e/kg, while silk fabric production showed a similarly high global warming potential of 80.9 kg CO_2e. Cotton fabric, by contrast, had lower emissions, averaging 14.9 kg CO_2e/kg of material. In cradle-to-grave analyses supported by SimaPro, polyester showed the highest impact, with an average global warming potential of 40.28 kg CO_2e/kg, compared to cotton (31 kg CO_2e/kg) and wool (30.94 kg CO_2e/kg). These values reflect the broader capabilities of SimaPro to integrate life cycle inventory data, including energy use, raw material extraction, use-phase activities (e.g., washing frequency), and end-of-life treatments such as reuse or incineration. SimaPro's compatibility with diverse impact assessment methods like IPCC, ReCiPe, CML, and TRACI further strengthens its versatility. For instance, TRACI was applied in studies using SimaPro 8.5.2, while ReCiPe and IPCC methods were applied in studies using versions ranging from 7.3 to 9.3. This flexibility enables detailed assessments of climate change impacts, energy demand, and water usage. Overall, SimaPro emerges as a validated tool for LCA in the textile sector, supporting evidence-based decision-making aligned with eco-design and circular economy principles.

The other software tool, GaBi is used in the textile industry to evaluate environmental impacts in different stages of textile production and recycling. In the paper (Sulochani et al., 2022) GaBi version 8 was used to model the environmental footprint of repurposing textile waste into composite materials. This application underscores GaBi's capability to handle complex recycling processes, offering insights into potential environmental benefits of innovative waste management strategies. The paper's findings, supported by GaBi's databases and modeling tools, highlight the software's role in promoting sustainable practices within the textile sector. However, specific quantitative impact values from this study are not provided in the available information. The paper (Dani and Shabiimam, 2024) aimed to evaluate the environmental impact of a textile company's operations. The GaBi 9.2.1 software was used in a gate-to-gate LCA of a Surat-based viscose textile company to evaluate its environmental performance across manufacturing stages, gray cloth production, dyeing, printing, and finishing. Using primary data collected directly from the facility and validated through mass and energy balances, the study revealed that the dyeing process accounted for the highest environmental impact. Dyeing alone contributed 38.04% of total energy demand and 28% of total water consumption, with a global warming potential of 5.37 kg CO_2-equivalents per kg of product. The weaving and finishing stages followed closely, with global warming potential contributions of 5.382 kg and 5.535 kg CO_2-eq, respectively. Atmospheric impacts assessed using CML 2001 and Environmental Footprint 2.0 methods showed that the dyeing stage also had the highest ozone depletion potential (3.32×10^{-16} kg R11-eq) and acidification potential (0.0475 kg SO_2-eq). Power-intensive sub-processes like thermosetting and jet dyeing were identified as hotspots due to their high steam and electricity requirements. For photochemical ozone creation potential, dyeing contributed 0.0472 kg ethene-eq, followed by weaving at 0.0133 kg. GaBi’s weak point analysis module enabled identification of these specific contributors, allowing targeted recommendations such as implementing cool pad dyeing to reduce energy use, installing zero-liquid discharge systems, and adopting renewable energy. Overall, this case study highlights GaBi’s capability to model complex textile operations and support strategic environmental management through quantified, process-specific impact assessments.

OpenLCA, an open-source software, has been applied in the textile industry to evaluate environmental and social impacts throughout product life cycles. A case study of an organic cotton hooded sweatshirt produced in India and used in Germany (GreenDelta, 2025a), (GreenDelta, 2025b). The study conducted a cradle-to-grave assessment, encompassing raw material extraction, manufacturing, distribution, use, and end-of-life stages. The findings revealed that the use phase, specifically the washing process, contributed to environmental impacts such as climate change and freshwater eutrophication. Scenarios altering user behavior, like reducing washing frequency or washing at lower temperatures, demonstrated potential for impact reduction. Additionally, a Social Life Cycle Assessment (S-LCA) using OpenLCA highlighted social risks associated with labor practices in the Indian textile sector, emphasizing issues like low wages and extended working hours. These insights show OpenLCA's capability to integrate environmental and social dimensions, aiding stakeholders in making informed decisions to improve sustainability in textile production and consumption.

Ecochain Mobius represents an environmental intelligence platform that enables companies to conduct LCA and measure the environmental impact of their products and processes. In the textile industry, Ecochain Mobius has been employed to assess and improve sustainability practices (Khanna et al., 2022), (Koščáková et al., 2024), (Pamu & Alugubelli, 2023). Dutch textile company, Schijvens Corporate Fashion, used Ecochain Mobius to analyze the environmental footprint of their workwear production. By inputting data related to raw material sourcing, manufacturing processes, transportation, and end-of-life disposal, Schijvens was able to identify significant environmental hotspots within their supply chain. The LCA revealed that fabric production and dyeing processes were major contributors to carbon emissions and water consumption. Armed with these insights, Schijvens implemented strategies such as selecting more sustainable materials, optimizing dyeing techniques, and improving logistics to reduce their overall environmental impact. This case demonstrates how Ecochain Mobius facilitates data-driven decision-making, allowing textile companies to pinpoint areas for improvement and track the effectiveness of sustainability initiatives over time. Similarly, the Belgian textile manufacturer, Beaulieu International Group, applied Ecochain Mobius to evaluate the environmental performance of their flooring products. The platform enabled Beaulieu to conduct comprehensive LCAs, uncovering that the use phase of their carpets had a substantial environmental impact due to maintenance requirements. As a result, the company focused on designing products that required less frequent cleaning and utilized materials that extended the product's lifespan, thereby reducing the overall environmental footprint.

Table 1. Comparative table with features of LCA software tools

Feature	SimaPro	GaBi	OpenLCA	Ecochain Mobius	OneClick LCA
User-friendliness	Designed for LCA professionals; may have a steeper learning curve for beginners.	Comprehensive features suitable for detailed analyses; may require extensive training.	Open-source platform with a user-friendly interface; suitable for both beginners and experts.	Built for business users with an intuitive interface, facilitating quick and reliable footprint assessments.	User-friendly interface customized for the construction sector; may require adaptation for textile applications.
Database integration	Integrates with extensive databases like Ecoinvent and Agri-footprint, providing a wide range of data for various industries, including textiles.	Offers a comprehensive Life Cycle Inventory database, beneficial for detailed textile industry analyses.	Supports multiple databases, including Ecoinvent and ELCD, offering flexibility in data selection.	Provides access to extensive environmental impact databases, such as Ecoinvent and the Dutch Nationale Milieudatabase at no extra cost.	Contains a vast database of construction materials; may require additional data integration for comprehensive textile assessments.
Cost	Pricing starts at approximately €5,900 per year; offers a free demo version for evaluation.	Pricing details are not publicly available; interested users need to contact the provider for a quote.	Open-source and free to use, making it a cost-effective option for organizations.	Annual subscription at €3,120; offers a free trial for users to explore its features.	Annual subscription priced at €3,720; provides a free trial for potential users.
Textile industry suitability	Suitable for detailed LCA studies in the textile sector; widely used by professionals for in-depth analyses.	Well-suited for comprehensive LCA analyses in the textile industry; offers detailed modeling capabilities.	Versatile tool applicable to various industries, including textiles; supports comprehensive LCA studies.	Customized for product footprinting in industries like apparel, consumer goods, and electronics; facilitates sustainable product design in the textile sector.	Primarily designed for the construction industry; may require customization for effective application in textile-related LCA studies.
Accessibility	Desktop application; may have limited cloud-based features.	Primarily a desktop application; cloud-based features are limited.	Desktop application with capabilities for collaborative work; supports various operating systems.	Cloud-based platform, ensuring accessibility and ease of collaboration across teams.	Cloud-based solution, offering accessibility and real-time collaboration features.

The translation of these insights into actionable strategies requires a multi-level governance and market-oriented approach. In high-impact sectors such as textiles, which contribute nearly 10% to global carbon emissions and over 20% to industrial water pollution, systemic change cannot be achieved through voluntary commitments alone. Therefore, a structured and enforceable policy framework is needed to scale circular practices, institutionalize sustainability metrics, and bridge the gap between assessment tools and industry-wide transformation. At the regulatory level, mandatory life cycle reporting and environmental product declarations should be introduced across textile value chains. Governments can require companies above a certain production threshold to disclose LCIA-based environmental performance indicators for lifecycle stages (e.g., raw material sourcing, dyeing, and end-of-life disposal). This aligns with the European Commission's Sustainable Products Regulation (2022), which mandates digital product passports and traceability, particularly for textiles. Such regulatory frameworks would improve transparency and comparability across supply chains, incentivizing lower-impact materials and processes. Extended producer responsibility schemes should also be expanded and refined to include LCIA-based benchmarks. For instance, producers could be taxed or subsidized based on their cradle-to-grave environmental footprint. This would encourage design for disassembly, modularity, and the use of recyclable or biodegradable fibres. The LCIA metrics, as outlined in this study, offer quantifiable thresholds for these performance-based incentives. For example, textiles emitting below 20 kg CO_2e/kg and using less than 4,000 Liters of water/kg during production could qualify for green-labelling or reduced compliance fees. Such economic instruments are vital in levelling the playing field and reducing the cost barriers to circular economy innovation. From an industry standpoint, LCIA provides companies with a strategic lens for eco-design, supply chain optimization, and innovation investment. Firms that integrate LCIA tools like SimaPro, GaBi, or OpenLCA into their R&D pipelines can prioritize raw materials with lower environmental intensity (e.g., mechanically recycled polyester, organic cotton) and identify high-impact production stages. The insights gained through LCIA can guide the development of closed-loop systems, such as take-back programs and fiber-to-fiber recycling, which not only reduce emissions but also open new revenue models (e.g., subscription-based clothing, resale, and remanufacturing). Case studies reviewed in this paper indicate that incorporating recycled fibers can cut GHG emissions by up to 50% and water usage by 70%, making a compelling business case for sustainable innovation. Capacity building and knowledge transfer must be prioritized, particularly for small and medium-sized enterprises in developing and transition economies, which often lack the technical and financial resources to implement LCIA tools. Governments, NGOs, and academic institutions should collaborate to establish LCIA training hubs and develop open-access circular economy toolkits. Policymakers and business leaders must act in concert to institutionalize lifecycle thinking and embed circularity across all levels of the textile ecosystem. This approach is needed for meeting international climate targets, decoupling growth from environmental degradation, and achieving long-term socio-economic resilience.

Conclusion

This paper provides a comprehensive assessment of how LCIA methodologies support the integration of circular economy principles within the textile industry, in alignment with the United Nations sustainable development goals. The findings demonstrate that LCIA is a critical decision-making tool that enables the identification of environmental hotspots across the textile lifecycle, from raw material extraction to end-of-life disposal, supporting evidence-based sustainability strategies. Quantitative insights from case studies show that transitioning from linear to circular models, specifically through fiber-to-fiber recycling and eco-design, can reduce greenhouse gas emissions by up to 50%, energy consumption by 30–40%, and water usage by as much as 70%. The use of LCIA tools such as SimaPro, GaBi, OpenLCA, and Ecochain Mobius shows their effectiveness in modelling complex processes, validating impact reductions, and guiding product development aligned with circular economy strategies. In addition to environmental benefits, circular economy adoption has socio-economic implications, including the potential to increase employment by 15% in the recycling and upcycling sectors. However, the analysis also reveals challenges in practical implementation, especially among incumbent textile companies facing organizational inertia, technological limitations, and supply chain fragmentation. These findings underscore the need for policy frameworks that incentivize sustainable practices, foster innovation, and enforce extended producer responsibility. LCIA, when coupled with circular economy, offers a scientifically grounded pathway for the textile industry to transition toward low-carbon, resource-efficient, and inclusive production systems that support the 2030 Agenda for Sustainable Development.

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