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CIRCULAR ECONOMY PRACTICES IN THE TEXTILE INDUSTRY: CURRENT STATUS, INDICATORS, AND DEVELOPMENT OPPORTUNITIES

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Abstract: The textile sector ranks among the largest industries worldwide, with its market value projected to reach USD 2.25 trillion by 2025. Rising environmental awareness has spurred increased efforts to adopt sustainable and circular production approaches. This research explores circular economy (CE) strategies within the textile and apparel industry, emphasizing resource optimization, recycling, renewable fiber usage, and digital innovations. Findings reveal that the type of technology employed, the scale of operations, and the degree of supply chain integration significantly affect CE implementation and the sector's sustainability outcomes. Additionally, the study highlights key challenges, success factors, and performance metrics, offering guidance for future research and policy initiatives. These insights are particularly useful for scholars, industry leaders, and policymakers seeking to advance CE practices in textiles.

Keywords: Circular economy, textile sector, sustainability, supply chain management, recycling, renewable fibers, resource efficiency, digital technologies, life cycle assessment, eco-friendly production, sustainable business models, product longevity, water conservation, energy efficiency, carbon footprint mitigation.

Introduction. The Intergovernmental Panel on Climate Change (IPCC) highlights that human activities, particularly the overconsumption of resources, are major drivers of greenhouse gas (GHG) emissions. The textile industry, a key global manufacturing sector, annually consumes around 98 million tons of non-renewable resources, including water, energy, chemicals, and fibers. Recycling rates in this sector remain low, with only 13% of clothing materials being reused. Worldwide, the textile industry contributes approximately 8–10% of total climate impacts and generates significant chemical and water pollution (Niinimäki et al., 2020).

Circular economy (CE) strategies, which focus on resource recirculation, product longevity, and sustainable supply chain management, are increasingly recognized as viable solutions to reduce environmental impacts while supporting economic development. According to Bocken et al. (2016), CE practices in textiles can lower raw material consumption, decrease waste, and foster sustainable business models such as leasing, repair, and resale. Digital innovations, including blockchain, IoT, and big data analytics, enhance traceability and optimize supply chain operations, thereby facilitating CE adoption (Geissdoerfer et al., 2020).

Traditionally, textile production relied heavily on cotton and synthetic fibers, with little attention paid to environmental consequences. Growing global demand, resource scarcity, and consumer awareness are now driving the adoption of renewable fibers, including Lyocell, bamboo, hemp, and recycled polyester. These alternatives require less water, energy, and chemicals during manufacturing, offering substantial environmental benefits.

Despite the inherent recyclability of textiles, a concerning 75% of waste still ends up in landfills globally. This trend carries significant environmental and economic consequences, placing the textile industry among the most polluting sectors, alongside fossil fuel production, mining, agriculture, construction, and healthcare. The industry is estimated to be responsible for about 8% of the global carbon budget and contributes roughly 20% of industrial water pollution. In 2020, textile collection and disposal costs in the United States exceeded $4 billion, based on average collection and disposal charges.

Textile production encompasses multiple stages, including fiber and yarn manufacturing, fabric creation, pretreatment, dyeing, printing, cutting, sewing, and quality control. Rapid industry growth has introduced social and environmental challenges, such as resource depletion, excessive textile waste, and unsustainable production practices. Consequently, the circular economy concept has emerged as a promising approach to transform the textile and apparel sector into a more sustainable industry by integrating key CE principles. CE also offers potential solutions for minimizing manufacturing waste while providing competitive advantages.

Minimizing waste at every stage of production is crucial for establishing a circular economy in textiles. By managing waste effectively and implementing sustainable strategies, the sector can improve resource efficiency and reduce its environmental footprint.

Cleaner production techniques, efficient wastewater management, and recycling processes offer opportunities to reduce waste during pretreatment. Limiting hazardous chemical use and lowering water consumption can decrease environmental impacts. Incorporating eco-friendly dyeing and printing methods, such as low-water or waterless dyeing and digital printing, can reduce chemical and water usage while minimizing ink waste. Innovative finishing techniques that require less energy and fewer chemicals, as well as mechanical or physical treatments like laser or ozone methods, further decrease waste.

Efforts to reduce waste continue through cutting and sewing operations. Digital technologies and pattern optimization can minimize fabric waste, while lean manufacturing principles reduce scraps during assembly. Using recyclable materials and sustainable accessories during trimming and assembly also helps limit waste. Strict quality control during production is essential to detect and correct defects early, preventing additional waste. The Green Lean Six Sigma approach provides a holistic method to optimize resources, reduce waste, and enhance sustainability while maintaining competitiveness.

Throughout the lifecycle of textile products, circular economy principles prioritize minimizing resource consumption, reducing waste, and mitigating environmental impacts. Recycling, reusing, and upcycling techniques enable the industry to maximize material value, improve resource efficiency, reduce waste, and foster innovative design approaches while supporting sustainability.

Key strategies include designing durable textiles, reducing resource use, and preventing overproduction. Extending the lifespan of garments through repair, refurbishment, or repurposing, as well as programs such as clothing swaps, thrift shops, and textile donations, helps divert materials from landfills. Mechanical processes like shredding and re-spinning fibers, along with chemical recycling methods, are essential for producing new materials from existing textiles. Designing products with recyclability in mind, using mono-materials, and eliminating non-recyclable components, such as metal buttons, further facilitates recycling. Incorporating recycled materials into production enables closed-loop systems, reducing resource demand and supporting a sustainable supply chain.

Collaboration among stakeholders—including suppliers, retailers, consumers, and regulators—is vital for successful CE implementation. Sharing knowledge, standards, and resources promotes innovation and accelerates the transition to a circular textile economy. Additionally, technology transfer, adoption of sustainable principles, and active collaboration between government, industry, and academia (the triple helix) support the sustainability process.

Fiber production can employ sustainable and regenerative agricultural practices to reduce chemical inputs and soil degradation, while recycling and reusing waste fibers generated during extraction further minimize waste. Optimizing yarn production through quality control reduces material loss and energy consumption, while promoting the use of sustainable and recycled fabrics in fabric production helps cut raw material waste. Mechanized fabric cutting, fabric nesting, and marker optimization improve fabric utilization and reduce offcuts, contributing to more efficient manufacturing processes.

Materials and Methods. This research utilizes a systematic literature review (SLR) in combination with an analysis of industry data. The methodology consists of three primary stages:

1. Literature Collection: Peer-reviewed publications from Scopus and Web of Science spanning 2018–2023 were gathered using search terms such as "circular economy," "textile sustainability," "eco-friendly fibers," "life cycle assessment," and "digitalization in textiles."
2. Data Analysis: Both quantitative and qualitative data were examined to assess mechanisms for CE implementation, relevant sustainability indicators, and potential obstacles. Key metrics included rates of material recycling, energy and water usage, carbon emissions, and overall supply chain efficiency.
3. Synthesis: The findings were integrated to reveal trends, identify success factors, and highlight industry challenges. Comparative analyses were conducted to determine how factors such as technology type, operational scale, and supply chain structure influence CE adoption.

In addition, corporate sustainability reports, industry surveys, and life cycle assessment (LCA) databases were reviewed to validate the findings and ensure their practical applicability.

To analyze the evolution of research in this field, the dataset was divided into two periods: 1975–2010 and 2011–2023. This allowed for the compilation of bibliometric data, including the most frequently cited articles, the most productive countries in terms of publications, and insights into highly active organizations and authors. Most of the bibliometric analyses were conducted using VOSviewer software. Additional sources, such as Journal Citation Reports (https://jcr.clarivate.com/ , accessed 11 September 2023), were used to identify journal impact factors, impact factors excluding self-citations, and journal publishers. The Web of Science interface was also employed to determine the affiliations of prolific authors; if no affiliation was provided, the first organization listed under "published organizations" was considered.

A co-authorship network map was generated with VOSviewer to visualize collaborative links between countries. The size of each node represents the number of articles published, while the thickness of connecting lines reflects the strength of collaboration. Each node is color-coded to indicate its cluster, with collaborations more likely to occur among countries within the same cluster.

Additionally, a journal citation network map was created, where nodes represent individual journals and edges indicate citation relationships. Journals grouped in the same cluster generally focus on specific subfields, helping researchers identify key publications in the area.

Keyword co-occurrence maps were also developed for each time period. In these maps, the size of each node corresponds to keyword frequency, the thickness of connecting lines shows the frequency of co-occurrence, and colors indicate clusters. Keywords that frequently appear together are grouped within the same cluster. Node colors reflect the average citation count for documents containing the keyword, with lighter (yellow) hues indicating higher citations and darker shades representing fewer citations.The methodological design of the current work is illustrated in Figure 1.

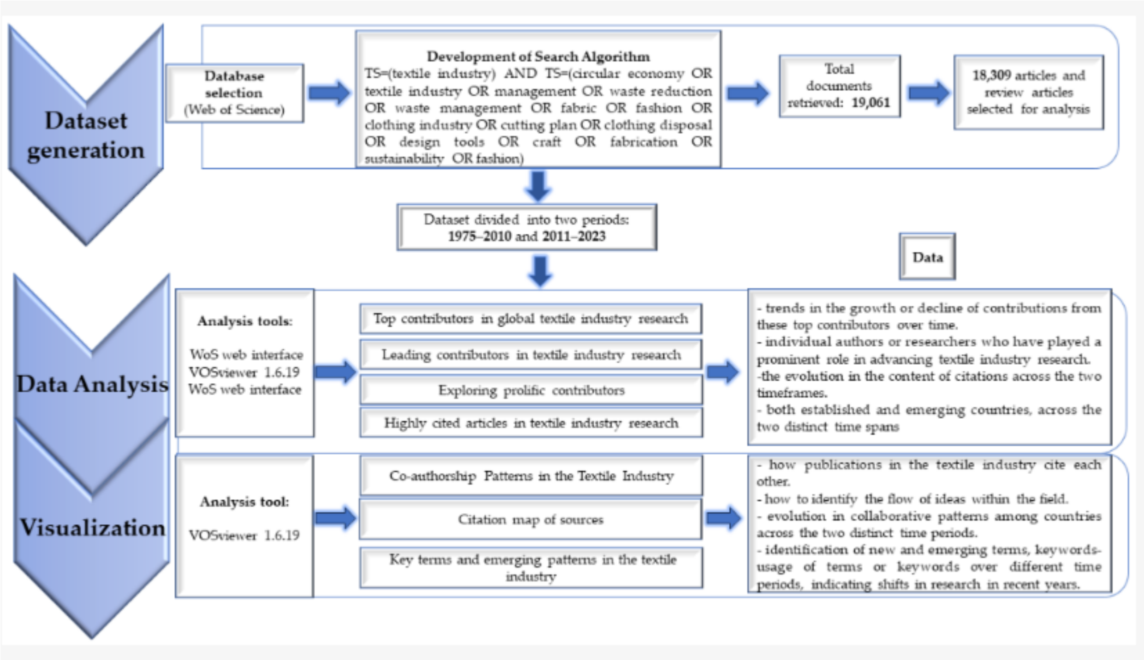

Figure 1. The methodological design of the bibliometric analysis

1. Material Efficiency and Recycling

The study shows that adopting CE practices significantly improves resource efficiency:

• **Fiber Recycling:** Companies employing recycled polyester reduce raw material consumption by 30–40%. For example, H&M's garment recycling program diverted over 20,000 tons of textiles from landfills in 2022.

• **Renewable Fibers:** Lyocell and hemp fibers consume up to 50% less water than conventional cotton (Ellen MacArthur Foundation, 2019).

• **Energy Savings:** Implementing CE practices in dyeing and finishing reduces energy consumption by 15–30%.

Carbon Emissions: Circular business models decrease GHG emissions by 15–20% per unit of product over the life cycle.

Table 1. Resource Consumption per 1 kg of Fiber

Resource	Conventional Fiber	Recycled/CE Fiber	Notes
Energy	160 MJ	110 MJ	Energy needed for fiber production
Water	10,000 liters	5,000 liters	Water required per kg fiber
Carbon Emissions	32 kg CO_2e	20 kg CO_2e	GHG emissions per kg fiber

2. Supply Chain Integration and Digitalization.

Digital solutions such as blockchain, IoT, and RFID tags are essential for CE adoption. These tools provide traceability, monitor material flows, and ensure compliance with sustainability standards.

• **Traceability:** Enables verification of recycled or renewable content in garments.

• **Inventory Optimization:** Reduces overproduction and waste by 15–25%.

• **Consumer Engagement:** Mobile apps provide product lifecycle data, encouraging sustainable purchasing.

3. Business Model Innovation

CE adoption drives innovative business models:

• **Leasing & Rental:** Rent-the-Runway reports 40% reduction in raw material use per product compared to traditional sales.

• **Repair & Refurbishment:** Patagonia's Worn Wear program extends garment life by up to 5 years.

• **Resale Platforms:** ThredUp and Poshmark enable second-hand sales, reducing landfill disposal and supporting consumer participation in CE.

These strategies not only reduce environmental impact but also enhance brand loyalty and profitability.

4. Regional and Sectoral Differences

CE adoption varies globally:

• **Europe:** High CE adoption due to strict regulations and consumer awareness. Up to 50% of recycled textiles in apparel are processed in the EU.

• **Asia:** Rapid industrial growth but fragmented supply chains slow CE integration. Investments in digital traceability are increasing in China and India.

North America: CE is promoted by large retailers and legislation encouraging recycling and resource efficiency.

Discussion

The findings indicate that CE adoption is influenced by:

• **Technology:** Advanced recycling, renewable fibers, and efficient dyeing methods improve sustainability.

• **Supply Chain Complexity:** Integrated digital systems facilitate collaboration among stakeholders.

• **Consumer Awareness:** Informed consumers drive demand for sustainable fashion.

• **Policy and Regulation:** Supportive government policies accelerate CE implementation.

Barriers include high initial investments, fragmented global supply chains, lack of technical expertise, and limited regulatory incentives. Companies that strategically integrate CE principles into corporate strategy achieve higher resource efficiency and competitive advantage (Murray et al., 2017).

Conclusion and Recommendations

Circular economy practices present a viable path toward sustainability in the textile industry. Key recommendations:

1. Promote the use of renewable and recycled fibers to reduce environmental footprint.
2. Integrate digital solutions for traceability and supply chain optimization.

3. Develop innovative business models like leasing, repair, refurbishment, and resale.
4. Encourage governments to implement regulations and incentives supporting CE adoption.

Conduct further research on CE indicators, barriers, and regional adaptation strategies.

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