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Bibliometric Analysis and Data Visualization: *Life Cycle Assessment* in Waste Management in the Textile Industry

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ABSTRACT

This study analyzes the development of literature related to the application of Life Cycle Assessment (LCA) in textile waste management using a bibliometric approach based on Scopus data for the period 2013–2024. Analysis using VOS viewer maps publication trends, keywords, citations, and author collaborations. The results show a significant increase in publications since 2014, dominated by journals such as Sustainability (Switzerland), Polymers, and Materials. The highest-cited articles highlight issues of the circular economy, microplastic pollution, and sustainable material innovation. The research focus has shifted from conceptual studies to technical solutions such as fiber recycling, eco-design, and circular fashion. Future trends point to the digitalization of LCA based on artificial intelligence, big data, blockchain, and decarbonization strategies for the textile industry. This research provides theoretical and practical contributions to policy development and the implementation of a sustainable textile industry in the future.

Keywords: *Bibliometrics, Circular Economy, Textile Industry, Life Cycle Assessment (LCA), Sustainability*

Introduction

The textile industry is one of the largest manufacturing sectors in the world, with a significant environmental impact [1]. Textile production involves high energy consumption, substantial water usage, and the use of chemicals that potentially pollute the environment [2]. In recent decades, the emergence of fast fashion has accelerated the cycle of clothing production and consumption, resulting in a massive volume of waste [3]. Globally, more than 92 million tons of textile waste are generated annually, yet only a small fraction is successfully converted back into new fibers, barely reaching one percent [4]. Reliance on a linear production model (cradle to grave) has intensified pressure on natural resources and environmental capacity, thereby demanding the development of more sustainable systems [5].

One of the most widely used scientific approaches to evaluate the sustainability of production systems is Life Cycle Assessment (LCA) [6], [7]. LCA assesses environmental impacts across the entire product life cycle, providing a more comprehensive sustainability analysis [8]. In the context of the textile industry, LCA can identify the most critical process stages that contribute to greenhouse gas emissions, energy consumption, and water pollution [9], [10], [11]. Such insights serve as the foundation for formulating mitigation strategies through eco-friendly materials, energy efficiency, and waste recycling, positioning LCA as both an evaluation tool and a strategic guide for sustainable practices in the textile sector [12].

Besides global issues, sustainability issues are also important at the national level. Indonesia is one of the largest textile producers in Southeast Asia, contributing significantly to national exports and employment [13]. However, the high volume of textile production is also accompanied by an increase in industrial waste, which has the potential to cause environmental pollution if not managed properly [14]. In this context, the application of Life Cycle Assessment (LCA) is an important instrument for assessing environmental impacts comprehensively, while supporting the transition of the Indonesian textile industry towards a circular economy and long-term sustainability [15].

The application of LCA in textile waste management remains limited, despite the complexity of this issue, which encompasses technical, social, economic, and policy aspects, as well as diverse types of waste such as solid residues, chemical discharges, and microplastics. All of which require integrated and sustainable management [16][17]. Although LCA has been widely applied to assess the sustainability of the textile industry, research specifically focused on textile waste management remains limited. This complexity demands a more integrated and interdisciplinary approach to bridge the knowledge gap, particularly in systematically mapping the stages of production, consumption, and final waste processing. Therefore, it is crucial to identify comprehensive research directions so that textile waste management strategies can be designed sustainably and aligned with the Sustainable Development Goals (SDGs) agenda. Although Grover et al. revealed that although LCA is extensively applied to assess textile sustainability, the aspect of waste management remains underexplored, necessitating systematic mapping to bridge the knowledge gap [18].

This study employs bibliometric analysis and data visualization to systematically trace the development of literature on the application of LCA in textile waste management, reviewing scientific contributions, research collaborations, and frequently used keywords [19]. The use of VOS viewer helps identify research gaps, allowing the study to focus more sharply while enriching the body of literature on textile industry sustainability and providing a strategic basis for environmentally conscious policies and industrial practices from 2015 to 2025.

Research Methods

This study employs a bibliometric analysis approach to examine the literature related to the application of Life Cycle Assessment (LCA) in textile waste management. The primary data source is Scopus, selected because it provides reputable scientific publications that have undergone a peer-review process [20], [21]. However, using a single database has limitations because it can exclude relevant literature from other databases, such as Web of Science or Dimensions. Therefore, further research is recommended to combine several databases for more comprehensive analysis results. The research stages were carried out sequentially, starting from the formulation of objectives and literature selection criteria, the development of keywords using Boolean operators, data collection, and filtering of articles according to the criteria [22]. The data were analyzed using VOS viewer to provide a comprehensive overview, which was then interpreted to identify research trends, collaboration patterns, and existing research gaps [23]. The research flow diagram in Figure 1. is presented to clarify the structured stages from beginning to end.

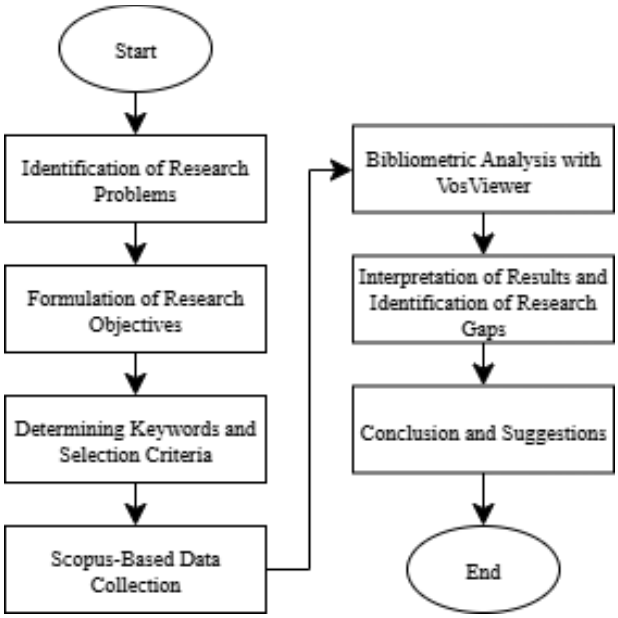

Figure 1. Research Flow

Results and Discussion

Determination of objectives and criteria

This research began with the formulation of objectives and the screening of Life Cycle Assessment literature in textile waste management using the highly reputable Scopus database [24]. The literature was selected based on topic relevance, period, characteristics, as well as issues of sustainability and waste management, while irrelevant or low-quality sources were excluded to maintain research focus [25][26]. To maintain transparency and avoid potential bias, the criteria for low-quality sources are explicitly explained, including: (1) publications without peer review; (2) articles without a Digital Object Identifier (DOI); (3) conference proceedings containing only abstracts; and (4) documents that do not discuss the application of Life Cycle Assessment (LCA) to textile waste management. This determination strengthens the validity of the methodology and ensures that the focus of the study remains directed towards relevant and credible scientific sources. The selected literature was then reviewed to identify keywords, themes, and research trends, which served as the basis for developing a more targeted search formula [27][28]. This strategy not only yielded a collection of relevant studies but also established a conceptual framework that illustrates the main challenges, strategic opportunities, and the development of studies [29] on the application of LCA in textile waste management, as summarized in Table 1.

Table 1. Research topic

Life Cycle Assessment	Waste Management	Textile Production Process	Sustainability
Life Cycle Inventory (LCI)	Textile waste management	Textile dyeing process	Circular economy
Life Cycle Impact Assessment	Wastewater treatment	Natural dyes	Green supply chain
Carbon footprint	Hazardous chemical reduction	Synthetic dyes	Cleaner production
Water footprint	Microplastics pollution	Fiber production (cotton, polyester)	Eco-design
Environmental impact assessment	Recycling textile waste	Batik production process	Industrial symbiosis
Comparative LCA	Landfill reduction strategies	Energy efficiency in textile industry	Sustainable textile economy
Social LCA	Waste-to-energy conversion	Biodegradable fibers	Extended producer responsibility (EPR)
Life Cycle Costing (LCC)	Chemical waste minimization	Smart textiles	Environmental regulation

Search keyword preparation

At this stage, the focus is directed toward the formulation of search keywords, which serve as the core instrument for systematically exploring the literature through academic databases [30]. The keyword formulation process was carried out by identifying relevant terms based on the main theme of the research [31]. This step aimed to ensure that the literature search process was more structured, comprehensive, and capable of capturing variations in terminology used across different scientific publications [32]. To optimize the results, Boolean operators (AND, OR, NOT), double quotation marks ("...") for phrases, truncation symbols (*) to accommodate word variations, and wildcards (?) for specific characters were employed [33], [34]. All search formulas were applied to the TITLE ABS KEY fields in the Scopus database as the primary repository, ensuring that the retrieved literature was relevant to the research topic and met credible academic standards [35]. Table 2 presents the keyword formulation to facilitate the retrieval of relevant literature.

Table 2. Search for the query rules

Rule	Topic	Keywords
1	*Life Cycle Assessment*	"Life-cycle-assessment" OR LCA OR "environmental*" OR "environmental-impact"
2	Waste Management	"waste*" OR "waste management" OR "textile-waste"
3	Textile Production	"textile*" OR "fabric* OR "garment*" OR "textile production" OR "fabric production" OR "garment production" OR "clothing production" OR "fashion production" OR "textile industry" OR "manufacturing process" OR "industrial production"
4	Sustainability	"sustainable*" OR "sustainable textile*" OR "green production" OR "sustainable manufacturing" OR "circular economy" OR "environmental sustainability"

Literature data collection

The literature collection was carried out through the Scopus database by utilizing a combination of keywords in the TITLE-ABS-KEY field [36]. The literature search process was conducted in three stages: an initial search without restrictions to obtain the broadest possible data coverage, screening based on document category, year, source, and language to eliminate redundant literature, and a final restriction to publications discussing the application of Life Cycle Assessment (LCA) in textile waste management, textile production, and sustainability issues [37]. A summary of these stages is presented in Table 3.

Table 3. Literature search stages

Step	Rule Combinations	Limitation	Number of Documents
1	Rule 1 AND Rule 2 AND Rule 3 AND Rule 4	-	7,105
2	Rule 1 AND Rule 2 AND Rule 3 AND Rule 4	- Publication Years: 2015-2025 - Document Type: Article - Source Type: Journal - Language: English - Open Access: All open access	1,421
3	Rule 1 AND Rule 2 AND Rule 3 AND Rule 4	Subject Area: - Environmental Science - Engineering - Materials Science	1,072

Bibliometric Analysis - Article trend analysis

The development of scientific literature in the fields of sustainability, circular economy, and resource management has been increasingly dynamic in the past decade, reflecting the great attention of academics and practitioners to global environmental issues such as climate change, ecosystem degradation, natural resource limitations, and waste and energy management. Scientific publications are a means of disseminating knowledge and indicators of global research directions, shown in Figure 2 with a significant increase since 2020 in line with the sustainable development agenda and environmentally friendly technological innovation.

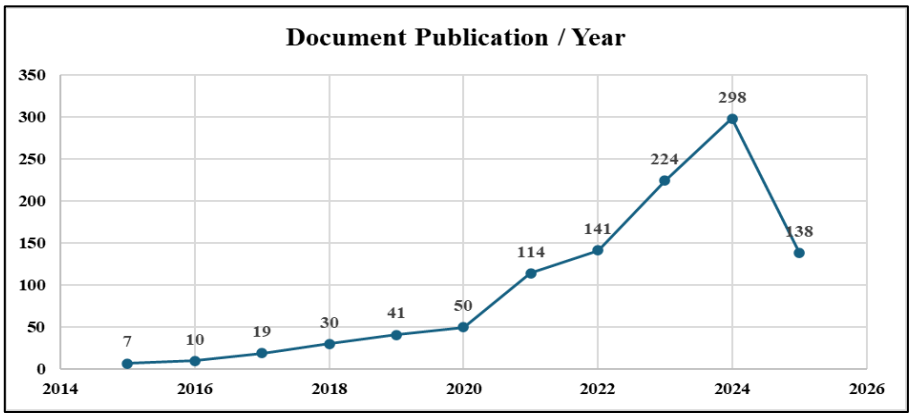

Figure 2. Publication trends

Based on Figure 2, the number of document publications per year shows a significant upward trend since 2014 with gradual growth in the initial period until it peaks in 2024 with 298 publications, before declining in 2025 to 138 publications. This pattern reflects the acceleration of research in the field of sustainability and the circular economy after 2020 which is influenced by the increasing urgency of global environmental issues and the sustainable development agenda, while the distribution of publications by journal as shown in Table 4 shows a shift in dominance with a surge in the contributions of a number of journals which indicates the increasing relevance of sustainability topics in the international academic realm.

Table 4. Top journals by publications

No.	Journal of Publications	2015-2020	2021 - 2025	Total Publications
1	Sustainability Switzerland	16	90	106
2	Journal of Cleaner Production	12	26	38
3	Polymers	3	35	38
4	Materials	4	32	36
5	ACS Sustainable Chemistry and Engineering	4	17	21
6	Science of the Total Environment	5	15	20
7	Resources Conservation and Recycling	5	14	19
8	Applied Sciences Switzerland	3	14	17
9	Waste Management	3	10	13
10	Desalination and Water Treatment	3	9	12
11	Energies	2	10	12
12	Journal of Environmental Management	2	10	12
13	Case Studies in Construction Materials	0	11	11
14	Results in Engineering	0	11	11
15	Chemical Engineering Journal	1	9	10
16	Buildings	0	9	9
17	Case Studies in Chemical and Environmental Engineering	1	8	9
18	Water Switzerland	2	7	9
19	Cellulose	0	8	8
20	Construction and Building Materials	2	6	8

Table 4 shows that the distribution of publications is dominated by Sustainability (Switzerland) with a total of 106 articles that jumped significantly in the period 2021–2025. A similar increase was also seen in Polymers and Materials, which experienced rapid growth compared to the previous period. Meanwhile, reputable journals such as the Journal of Cleaner Production have remained consistent despite a more moderate increase. Several new journals are also starting to contribute with a relatively significant number of articles, signaling a shift in research focus towards multidisciplinary journals that strengthen the position of sustainability as a global strategic theme. Furthermore, the quality and influence of publications are reflected in

Table 5 which summarizes the 20 articles with the highest citations. The information shows that the issues of circular economy, plastic pollution, textile waste management, and sustainable material innovation are the most prominent and widely referenced topics in the international academic community.

Table 5. Highly cited relevant publications

No.	Title	Year of Publication	Research Topics	Total Quoted
1	A critical review of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies [38]	2021	Examining the impact of COVID-19 and the circular economy model.	650
2	Cellulose nanomaterials in water treatment technologies [39]	2015	Evaluating cellulose nanomaterials for sustainable water treatment.	629
3	Microfibers from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment [40]	2019	Review textile microfiber emissions and microplastic pollution.	490
4	Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling [41]	2020	A model of chemical recycling for the environmental impact of plastics.	292
5	Sustainability considerations in membrane-based technologies for industrial effluents treatment [42]	2019	Evaluate membrane technology to treat industrial liquid waste.	288
6	Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications [43]	2017	Assess the environmental impact of additive vs conventional manufacturing.	265
7	Design, management and control of demanufacturing and remanufacturing systems [44]	2017	Smart de- and remanufacturing systems for the circular economy.	240
8	Critical success factors for a circular economy: Implications for business strategy and the environment [45]	2020	Success factors of the circular economy of the leather supply chain.	224
9	Recycled nylon fibers as cement mortar reinforcement [46]	2015	Nylon recycled fish nets for sustainable cement mortar.	223
10	Identifying critical supply chains and final products: An input-output approach to exploring the energy-water-food nexus [47]	2018	Analysis of the input-output of the energy, water, food supply chain.	195
11	Exploring the role of lean thinking in sustainable business practice: A systematic literature review [48]	2017	Lean and green for sustainable corporate environmental performance.	191
12	Food waste drivers in Europe, from identification to possible interventions [49]	2017	Causes of European food waste and reduction recommendations.	178
13	Eco-sustainability of the textile production: Waste recovery and current recycling in the composite's world [50]	2021	Application of recycled textile fibers in circular composites.	160
14	Textile-apparel manufacturing and material waste management in the circular economy: A conceptual model to achieve sustainable development goal (SDG) 12 for Bangladesh [51]	2022	Bangladesh's textile waste management model is circular based.	155
15	United States plastics: large flows, short lifetimes, and negligible recycling [52]	2021	U.S. plastic material flows and recycling challenges.	148
16	MXene Enhanced 3D Needled Waste Denim Felt for High-Performance Flexible Supercapacitors [53]	2024	Waste denim and MXene for flexible supercapacitors.	143
17	Implementing circular economy in the textile and clothing industry [54]	2021	Challenges and interventions of the Asian textile circular economy.	142
18	Repurposing of Fruit Peel Waste as a Green Reductant for Recycling of Spent Lithium-Ion Batteries [55]	2020	Orange peel waste for lithium battery recycling.	139
19	Eco-efficiency assessment of manufacturing carbon fiber reinforced polymers (CFRP) in aerospace industry [56]	2018	An ecological-economic model of carbon fiber polymer production.	138
20	Consumers' value and risk perceptions of circular fashion: Comparison between secondhand, upcycled, and recycled clothing; [57]	2021	Consumer perception of circular fashion products from waste.	136

Based on

Table 5, the articles with the highest citations highlight global strategic issues such as the impact of COVID-19 on the economy and circular economy opportunities (650 citations), cellulose nanomaterials for water treatment (629 citations), and microplastic pollution from textiles (490 citations). This shows that research that contributes to global environmental challenges is receiving wide attention. The dominant themes include plastic recycling, textile waste management, organic waste utilization, and circular economy models. In the 2021–2024 period, the focus shifts to innovative technology applications such as circular fashion, lithium battery recycling, and denim supercapacitors, confirming the research trend towards sustainable practical solutions.

Co-authorship visualization analysis

In bibliometric research, co-authorship analysis is used to map the pattern of author collaboration in a field, identify groups that are connected through publications, measure the intensity of relationships, and find the main actors connecting networks. This network map shows the dynamics of academic collaboration as well as the distribution of knowledge contributions in the scientific community.

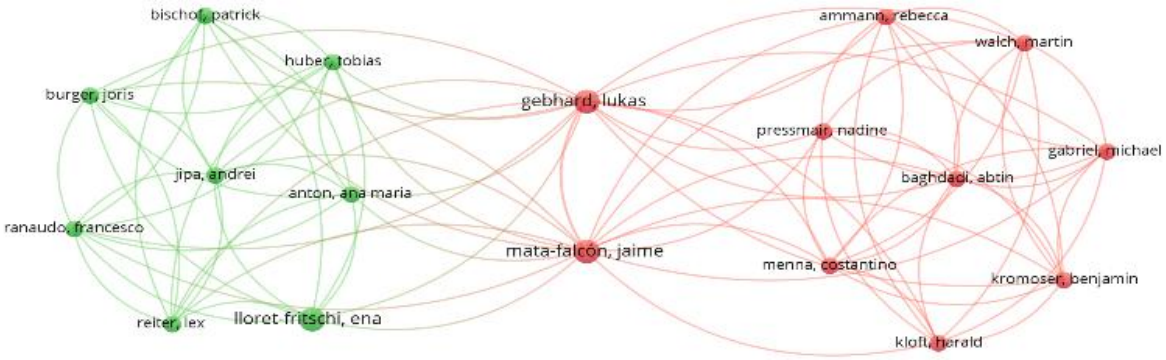

Figure 3. Co-authorship visualization

The visualization results in Figure 3 using VOS viewer show two main clusters, namely green and red. The green cluster represents authors with close collaboration, while the red cluster shows authors with similar patterns of interconnectedness. Two authors, Getchell, Kristin and Marcal Felipe Jaime, act as a connecting node connecting the two clusters. This position affirms their important role in strengthening the integration of scientific networks and encouraging the exchange of ideas across research groups.

Keyword visualization analysis

Bibliometric analysis functions to trace publication trends while identifying dominant conceptual constructions through keyword mapping. Keyword visualization represents the interconnectedness of terms that often appear together, so that researchers can comprehensively understand the main theme. This approach helps to identify research directions systematically, making keyword visualization analysis an important instrument to uncover established study focuses and find open academic exploration spaces.

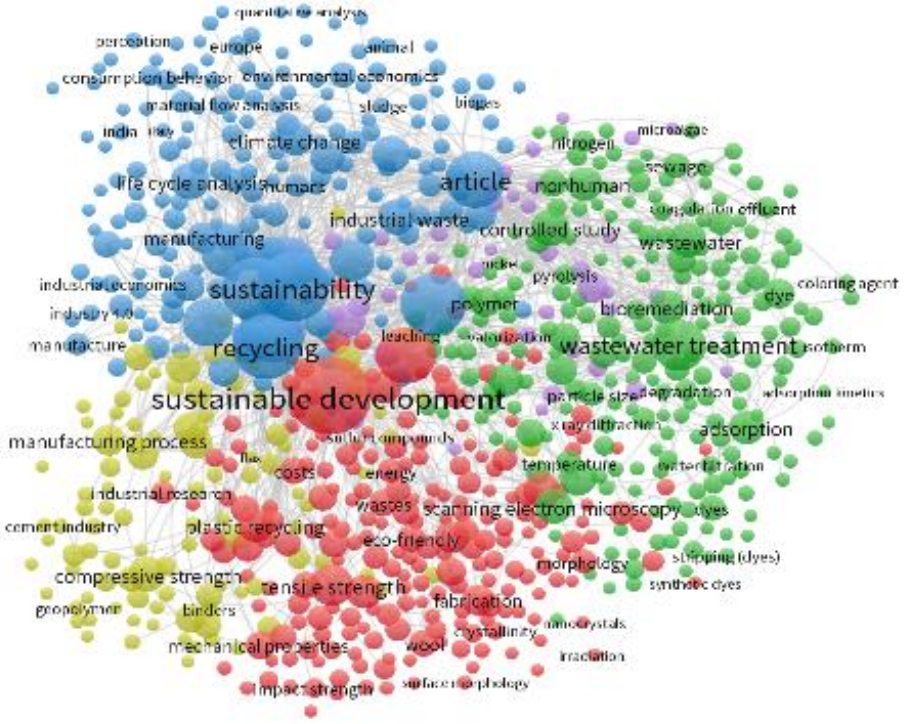

Figure 4. Keyword visualization

The visualization in Figure 4 shows some of the main clusters of the research theme. The keywords sustainability, sustainable development, and recycling are the dominant nodes. The blue cluster is related to resource management and the circular economy, red is related to policy, environment, and energy, green is to sustainable consumption and production, and yellow is to the methodological approach. Overall, sustainability studies develop in a multidisciplinary manner with strong thematic linkages and open opportunities for interdisciplinary studies.

Interpretation of results

Bibliometric analysis shows that *Life Cycle Assessment* research on textile waste has increased since 2014 and peaked in 2024, reflecting the global urgency for *sustainability* and *circular economy*. This increase was triggered by awareness of the impact of the textile industry on energy, microplastic pollution, chemical waste, and water use. Research trends have shifted from concept to practice, including *eco-friendly materials*, fiber recycling, *circular fashion*, and the application of *LCA* to *carbon footprint*, *water footprint*, and social aspects. The dominance of key keywords and new themes such as *eco-design*, *EPR*, and *industrial symbiosis* confirms the direction towards a sustainable textile business.

Table 6. Research development

Year	Focus of Research	Explanation
2010–2015	Conceptual study of LCA, measurement of the environmental impact of textiles (water, energy, chemical).	Research in this period is still predominantly conceptual, focusing on early mapping of the environmental impact of textile production processes, especially the use of water, energy, and hazardous chemicals.
2016–2020	Emphasis on fiber recycling, microplastic pollution, industrial liquid waste, nanomaterials.	The study began to emphasize technical solutions through textile fiber recycling, microplastic pollution issues from clothing, industrial liquid waste treatment, and exploration of nanomaterials to support production sustainability.
2021–2025	Circular fashion, eco-design, textile waste → energy, material innovation (MXene, biopolymer), and circular economy-based business models.	The focus of research shifts to the application of circular economy concepts and sustainable material innovation. LCA is used to assess circular fashion, eco-friendly design, utilization of textile waste into energy, and circular business models.
2026–2030 (*Prediction*)	The digital integration *of LCA* with AI and big data, the application of blockchain for textile supply chain transparency, cross-border socio-economic LCA, as well as a focus on decarbonizing the textile industry through renewable energy.	The research is expected to be further advanced by integrating AI and big data for real-time LCA analysis, the use of blockchain to improve supply chain transparency, expansion to the global socio-economic dimension, as well as decarbonization strategies towards *net zero emissions*.

After 2025, LCA studies in the textile industry are expected to evolve towards digital, integrated, and global. Technologies such as Artificial Intelligence, machine learning, big data, and blockchain will accelerate environmental analysis and improve supply chain transparency. The focus also shifts to social LCA to assess the socio-economic impact across countries, especially in developing countries. Decarbonization through renewable energy and a net zero emission strategy are the main agenda towards the global target of 2030.

Managerial Implications

These findings underscore the importance of implementing circular economy strategies by the textile industry to maintain sustainability while maintaining competitiveness. Through the implementation of LCA, managers can identify critical points in the production process to formulate energy efficiency policies, the use of environmentally friendly materials, and an integrated waste management system. Furthermore, the development of LCA's digital integration with AI and blockchain opens up opportunities to improve supply chain transparency, strengthen regulatory compliance, and build a positive image in the eyes of global consumers who are increasingly concerned about sustainability issues.

Theoretical Contributions

Theoretically, this study expands the LCA literature by emphasizing that sustainability studies in the textile industry are now more applicable and multidisciplinary. His main contribution is in the form of research mapping that connects technical issues such as fiber recycling, eco design, and renewable energy technology with socio-economic aspects such as social LCA, extended producer responsibility, and circular business models. This research enriches the theory of sustainability by placing LCA as an integrative instrument that connects technical, managerial, and public policy aspects to support the transition to a low-carbon, inclusive, and circular economy-based textile industry.

Conclusion

The results of the bibliometric analysis show that research related to the application *of Life Cycle Assessment* (LCA) in textile waste management has experienced rapid growth since 2014, with a peak of 298 publications in 2024 before decreasing to 138 in 2025. The distribution of publications was dominated by the journal *Sustainability (Switzerland)* with 106 articles, followed by *Polymers* and *Materials* which also showed a significant surge. The article with the highest citations reached 650 citations, discussing the impact of COVID-19 on the global economy and circular economy opportunities. The thematically, the focus of research shifted from conceptual studies (2010–2015) to technical solutions for fiber recycling, microplastic pollution, and nanomaterials (2016–2020), then to circular fashion, eco-design, and sustainable material innovation (2021–2025). The future trend (2026–2030) is projected to lead to the digitization of LCA based on AI, big data, blockchain, and the textile industry's decarbonization strategy. This study has limitations in the use of one database, namely Scopus, which has the potential to limit the reach of literature from other sources; therefore, further studies are recommended using a multi-database approach so that the mapping results are more comprehensive and representative.

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