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Implementing Circular Economy Elements in the Textile Industry: A Bibliometric Analysis

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Abstract: Significant environmental and social issues confront the textile and apparel industries, including resource depletion and excessive textile waste. Implementing circular economy principles is essential for the sustainability of this industry. The present paper is a bibliometric analysis study type designed to identify collaborative networks, prolific countries, journals, and influential articles pertaining to the implementation of the circular economy in the textile and apparel industries that may serve as a starting point for an in-depth understanding of the subject, facilitating the knowledge of essential bibliometric parameters for pre-publication phases. The data were extracted from the Web of Science and analyzed using both the Web of Science web interface and the VOSviewer software version 1.6.19. The bibliometric data were divided into two distinct periods to analyze the evolution of this subject over time: from 1975 to 2010 and from 2011 to 2023. In the first period, the most productive country was the United States, with 527 publications, accounting for 10.81% of the scientific output during that time. In the second period, China emerged as the most productive country, with 2478 published documents, constituting 18.44% of the total production in this period. During the first period, Istanbul Technical University was the most active institution, with 91 publications (1.87% of the total production), while in the second period the Indian Institute of Technology System was the most productive, with 265 documents (1.95%). These key findings demonstrate the textile industry's commitment to sustainable and environmentally friendly practices. They also highlight the industry's adoption of advanced technologies and its exploration of new research areas; but there is still room for improvement, which is why continuous research implemented through future research areas is essential.

Keywords: bibliometric analysis; textile industry; circular economy; textile waste; waste reduction; sustainability

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1. Introduction

Despite the inherent recyclability of textile waste, an alarming 75% of such waste finds its way into landfills on a global scale [1]. This disconcerting trend carries profound implications, both from an environmental and economic standpoint, effectively positioning the textile industry as one of the most environmentally deleterious sectors [2], alongside other detrimental industries such as the fossil fuel industry [3,4], mining activities [5], agriculture [6], construction [7–9], and the medical field [10,11]. The textile industry bears a substantial environmental responsibility, responsible for an estimated 8% of the entire global carbon budget and playing a significant role in industrial water pollution, contributing to approximately 20% of such pollution [12]. In 2020, the expenses associated with the collecting and disposing of textiles in the United States amounted to more than $4 billion, as calculated using average disposal charges and collection expenditures [13].

The textile sector is an integral part of the worldwide economy, encompassing various phases of production, such as fiber and yarn production, fabric production, pretreatment to remove impurities, dying, printing, cutting, and sewing, as well as quality control. However, the rapid growth of this industry has brought about significant social and environmental concerns, including resource depletion, excessive textile waste, and unsustainable manufacturing processes. In consequence, the concept of a circular economy has emerged as an intriguing approach for transforming the textile and apparel industry into a sustainable one by integrating essential components into its operations [14]. Furthermore, the concept of the circular economy possesses substantial potential for mitigating manufacturing waste issues and presenting an advantageous competitive solution [15].

Decreasing textile waste at each stage of manufacturing is essential to establishing a circular economy in the textile industry. By managing waste generation and adopting sustainable strategies, this sector can increase resource efficiency and reduce its environmental impact [16].

The manufacturing procedure begins with fiber production, in which sustainable and regenerative agricultural methods can be used to reduce waste from chemical inputs and soil degradation. In addition, investigating novel approaches for recycling and reusing the waste fibers generated during fiber extraction can contribute to waste reduction. During yarn production, it is essential to optimize processes to reduce material waste and energy consumption. This outcome can be accomplished by employing quality control measures to minimize defects and maximize yarn usability. To reduce raw material waste, emphasis should be given to supporting the utilization of sustainable and recycled textiles in fabric production. Utilizing effective manufacturing techniques, such as mechanized fabric cutting, can reduce fabric waste, while techniques such as fabric nesting and marker optimization may improve fabric utilization and decrease offcuts [17,18].

Through the implementation of cleaner production methods, efficient treatment of wastewater, and recycling procedures, pretreatment processes provide opportunities for waste reduction. The environmental impact of pretreatment operations can be reduced by limiting the use of hazardous compounds while decreasing water consumption. Incorporating eco-friendly techniques into the dying and printing processes allows for waste reduction. Low-water or waterless dyeing procedures can reduce water consumption and chemical waste, while digital printing techniques offer precise color application, thereby minimizing ink and water waste. Implementing novel finishing strategies that involve fewer chemicals and less energy may lead to a decrease in waste. Mechanical and physical refining techniques, such as laser or ozone treatments, can reduce the use of chemicals and waste [19,20].

Efforts to reduce waste continue throughout the cutting and stitching processes. By improving the cutting process with digital technologies and pattern engineering, textile waste can be reduced, while principles of lean manufacturing can reduce fabric scraps produced during sewing and assembly. Examining different materials and accessories with an emphasis on recyclable materials and sustainability may lead to a decrease in waste during the assembly and trimming stages. To reduce the amount of waste generated by these processes, efficient production methods should be utilized. During the production process, it is essential to implement stringent quality control measures to detect and correct defects promptly, thereby minimizing waste [21,22]. Moreover, Green Lean Six Sigma is a holistic approach that optimizes resource use, minimizes waste, and promotes sustainability in manufacturing. It helps industries remain competitive while ensuring eco-conscious practices [23].

Throughout the entire life cycle of textile items, circular economy principles prioritize minimizing the utilization of resources, reducing the generation of waste, and alleviating the effects on the environment. Utilizing techniques like recycling, reusing, and upcycling, the textile and apparel industries implement circular economy principles in order to maximize the intrinsic worth of materials and products. By doing so, the industry can significantly

improve resource utilization, waste reduction, and versatility in design while fostering sustainability [24–26].

The first stage is to reduce textile waste through the adoption of sustainable production procedures, such as the design of durable and long-lasting textiles, the use of fewer resources during production, and the minimization of overproduction. Another essential aspect is supporting the reuse of textiles, which involves extending their lifecycle via repair, refurbishment, or repurposing. Initiatives like garment swaps, thrift shops, and textile donation programs aid in the removal of textiles from landfills. Utilizing mechanical techniques such as shredding and re-spinning fibers or chemical methods to break down textiles into basic elements for the production of new materials is essential. Designing textiles with recycling in mind, utilizing mono-materials or easily separable resources, and removing non-recyclable components such as metal closures and buttons facilitates the process of recycling even further. By incorporating recycled materials back into textile production, establishing closed-loop systems decreases the need for resources and supports a more sustainable supply chain. Collaboration between stakeholders, including suppliers, retailers, customers, and legislators, is crucial for the successful implementation of the circular economy. By exchanging information, standards of excellence, and resources, innovation can be promoted, and the transition to a circular textile economy can be accelerated [27–29]. Moreover, the process of sustainability is facilitated by the transfer of technology, the implementation of sustainable principles, and the increased activity and interaction of the triple helix (governments, the textile industry, and universities) [30,31].

The transition from a linear economic model to a circular economy necessitates active participation and a firm commitment from stakeholders, coupled with a comprehensive overhaul of systems to align with the principles of innovation in business models [32].

Numerous evaluations have delved into the association between the circular economy and digital technologies to ascertain the role that digital technologies play in bolstering the implementation of circular economy [33–35]. The advent of advanced digital manufacturing technologies has opened up new avenues for the effective utilization of circular resources, waste management, and green technology [36,37].

The swift advancement of digital technologies harnesses the power of automation and data exchange within the realm of smart manufacturing and production processes. This has the dual benefit of reducing excessive consumption and minimizing production errors while concurrently enhancing overall efficiency, thereby propelling sustainable development [34].

A set of ten pivotal digital technologies have been identified and evaluated for their potential to facilitate a circular economy implementation. These technologies encompass additive/robotic manufacturing, artificial intelligence, big data and analytics, blockchain technology, three-dimensional information modeling, digital platforms/marketplaces, digital twins, geographical information systems, material passports/databanks, and the Internet of Things [38]. Moreover, industry 5.0 is a concept that seeks to harness the capabilities of advanced technologies like artificial intelligence, the Internet of Things, and robotics to create more flexible, efficient, and sustainable production systems where humans and machines work together harmoniously [39,40].

Digital technologies hold the capacity to play a pivotal role in advancing the circular economy by meticulously tracking the flow of products, components, and materials. Moreover, they provide invaluable data that enhance resource management and bolster decision-making across various phases of the industry life cycle. To illustrate, the Internet of Things can facilitate automated tracking and monitoring of natural capital. Big data significantly contributes to various aspects of circular strategies, such as optimizing the matching of waste with available resources in industrial symbiosis systems through the real-time collection and processing of input–output flows. Furthermore, data analytics, often referred to simply as analytics, serves as a versatile tool capable of predicting product health and wear, minimizing production downtime, streamlining maintenance schedules, expediting spare parts procurement, and optimizing energy consumption [41].

Blockchain technologies have emerged as one of the most transformative technological tools, poised to revolutionize the operational landscape of supply chains. By enhancing traceability, coordination, and sustainability within supply chains, BTs offer substantial assistance to supply chain managers [42]. However, digital technologies have emerged as catalysts for the integration of circular economy principles, fostering sustainable development within the textile industry [43].

Research Objectives

In the context of implementing circular economy principles in the textile and apparel industries, bibliometric analysis may play a crucial role in shedding light on the scientific investigations conducted in this field. To the extent of the research team's awareness, the current analysis is the first to use this particular algorithm within this specific field of study. The design and objectives of this study are based on the advantages of comprehensive bibliometric analyses: using data-driven methods for evaluating research output, impact, and trends in the field; identifying the most influential publications, authors, journals, countries, and institutions in the field; assessing the impact of a publication in the field by examining the number of citations; identifying patterns of collaboration between institutions, countries, and researchers; exposing the most influential publications in the field that can lead after further study to the identification of research gaps and future research directions; and presenting a global perspective on research activity in the field, which can be a time-saving tool for researchers, academics, and students in the pre-selection or improvement stages of research topics as well as for those encountering a research obstacle in the field that can be solved by access to the most prolific researchers, institutions, and countries in the field. Therefore, the aim of the present paper is to conduct an in-depth bibliometric analysis of the implementation of circular economy principles in the textile and apparel industries. In addition, the article seeks to emphasize the originality and significance of this research, focusing on the industry's potential for waste reduction and sustainable practices.

2. Materials and Methods

Comprehending publication trends, assessing research impact, and delving into specific study domains necessitate bibliometric analysis. In this type of research, employing the appropriate search methodology and source database is paramount. The Web of Science (WoS) offers comprehensive coverage across a wide array of research fields and disciplines. This extensive coverage enables us to access a diverse range of scholarly papers that significantly contribute to our areas of interest: the textile industry, the circular economy, and sustainability. Additionally, the WoS provides in-house bibliometric analysis tools that provide valuable data, thereby enhancing the quality of our article. Bibliometric studies have a substantial advantage over other methods of analyzing the literature within a field, allowing for the quantitative examination of a vast number of documents, focusing on parameters such as citations, the frequency of key terms, and collaborative networks. This enables the discovery of field trends, pinpoints impactful research, and uncovers prospective collaboration networks. The decision to use bibliometric analysis over other methodologies is based on its potential to provide a more data-driven, comprehensive, and objective view of the state of research in our chosen topic [44,45]. Our search was designed to explore literature trends related to the textile industry, circular economy, and sustainability. To achieve this, we employed the following search algorithm: TS = (textile industry) AND TS = (circular economy OR textile industry OR management OR waste reduction OR waste management OR fabric OR fashion OR clothing industry OR cutting plan OR clothing disposal OR design tools OR craft OR fabrication OR sustainability OR fashion). The search algorithm yielded a substantial number of documents, totaling 19,061, with the majority written in English (17,837). Following closely is German (313). Other languages with notable contributions include Croatian (186), French (144), and Spanish (144). Additionally, Portuguese (101), Japanese (64), Turkish (53), Chinese (49), and Russian

(33) also made significant contributions to the dataset. In terms of document types, the most prevalent are articles (14,062), followed by proceeding papers (3196), and review articles (1566). Other document types in the dataset include book chapters (418), early access publications (371), book reviews (364), and editorial materials (254), with other categories having under 100 documents included in them.

A few of the many categories included in the collection show a lot of study activity and have over 1000 documents each. These categories cover a wide range of disciplines and subjects, which greatly aids in thoroughly investigating the textile sector, circular economy, and sustainability. Notable categories include Environmental Sciences (2838 documents) and Materials Science Textiles (2659 documents), which top the list. Furthermore, Engineering Chemical (1738 documents) and Engineering Environmental (1594 documents) represent pivotal domains. Each item can be categorized into several categories, as shown in Figure 1's visual representation of the top 10 most notable categories.

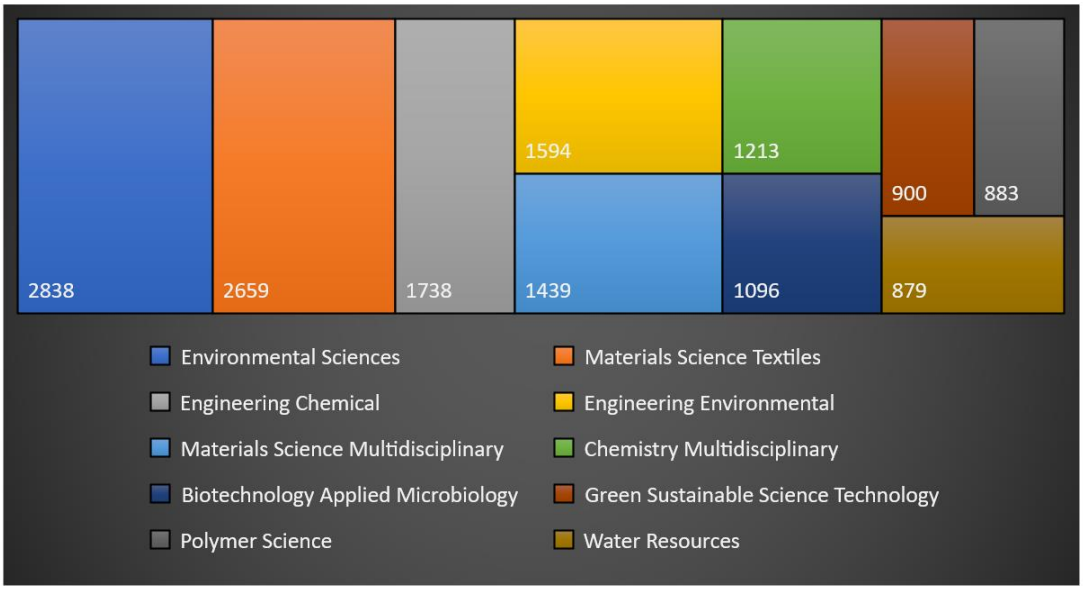


Figure 1. Multi-category document distribution.

The 18,309 documents included in this study were all articles, review articles, and proceeding papers written and published in the aforementioned languages. This research made use of the integrated analytical tools available through the WoS web interface, along with VOSviewer version 1.6.19. The WoS web interface's export function was used to export tab-delimited files with thorough record details in order to obtain the necessary data for the bibliometric analysis [46].

To follow the evolution of this field, the dataset has been divided into two distinct periods. The first period covers the years from 1975 up to 2010, and the second period covers the years from 2011 to 2023. As a result, bibliometric data on the most cited papers, the most prolific countries that produced documents during these periods, and the insights into organizations and authors that demonstrated exceptional output in this field have been compiled. Most of the information was generated and analyzed using the VOSviewer program. Additional sources, such as the *Journal Citation Reports* (https://jcr.clarivate.com/ accessed on 11 September 2023), were employed to identify factors like impact factor, impact factor excluding self-citations, and journal publishers. Furthermore, the WoS interface was utilized to determine the organizations to which the most prolific authors belong. It is worth noting that if no affiliation is presented for an author, we consider the first organization listed in the "published organizations" section of the WoS interface.

A network map that depicts the co-authorship-based collaborative linkages between nations was generated using VOSviewer. The number of articles published is represented

by the size of each node on the map, and the thickness of the connecting lines indicates the degree of cooperation between the two nations. Each bubble has a unique color allocated to it that denotes its participation in a particular cluster. Research collaboration is more likely to occur between nations that belong to the same cluster.

A network map of journal citations was created using VOSviewer, with nodes denoting distinct journals and connections denoting citation relationships. Journals that are categorized into clusters specialize in particular subfields. These maps prove to be very useful for researchers aiming to identify key journals in this field.

Keyword co-occurrence network maps were generated for each time period. In these maps, the size of each bubble corresponds to the frequency of occurrences, the thickness of the line connecting two keywords reflects the frequency of co-occurrence, and the color indicates the cluster. Keywords that frequently appear together tend to be grouped within the same cluster. Keyword node maps were created for each period; the color of each circle is influenced by the average number of citations of all the documents that include the keyword, while the size is related to the number of occurrences. Lighter colors, especially yellow, indicate a higher number of citations, while darker colors indicate fewer citations.

The methodological design of the current work is illustrated in Figure 2.

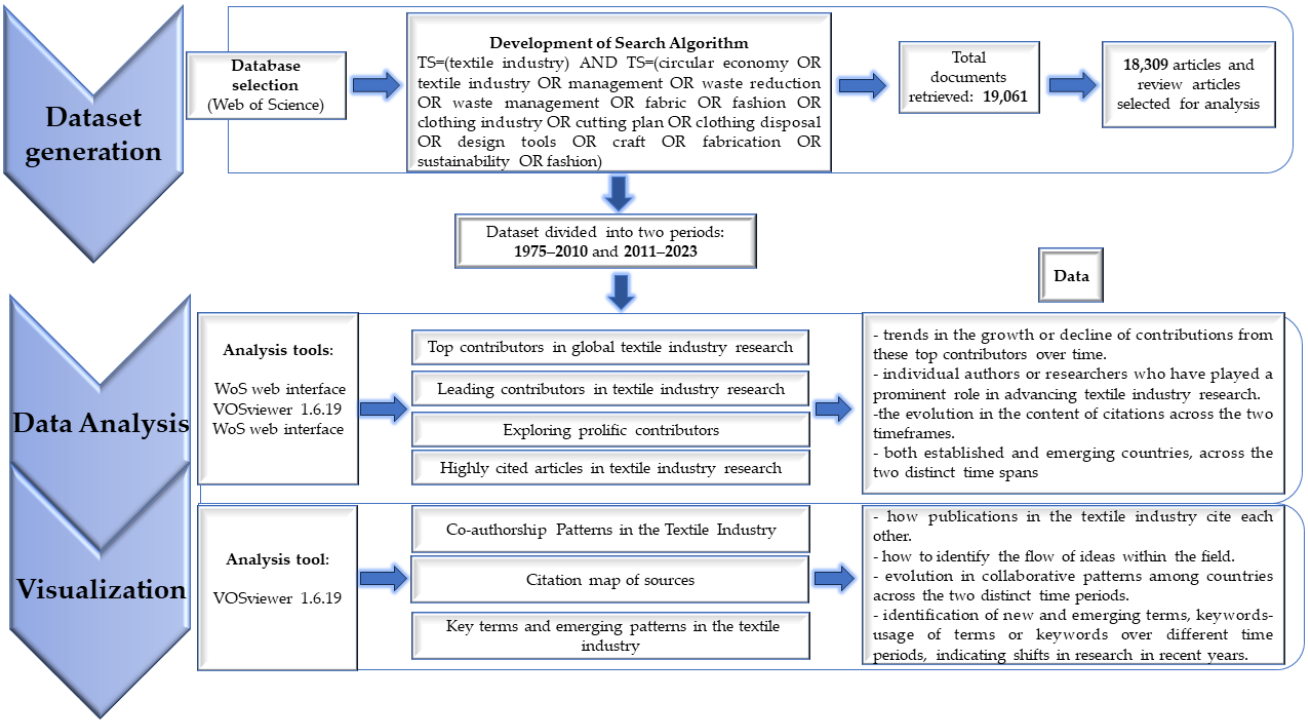


Figure 2. The methodological design of the bibliometric analysis.

3. Results

In Figure 3, the number of articles published in this field over time is presented. It is noteworthy that the first year in the graph is 1996 because that is when over 100 documents were first published, highlighting the upward trend in the number of articles in this field. On average, we can observe that the number of articles has tended to increase from year to year, except for a slight decrease between 2011 and 2014. However, starting from 2015 there has been a consistent upward trend in the number of published articles, thus suggesting an increasing interest in this field.

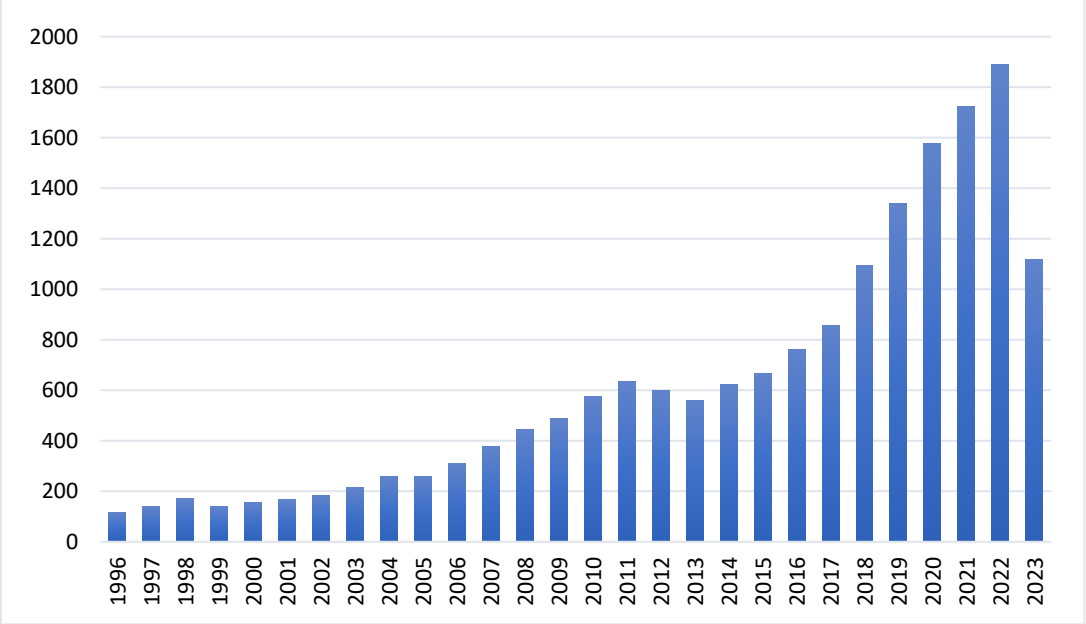


Figure 3. A timeline of published documents.

3.1. Period 1975–2010

3.1.1. Top Contributors in Global Textile Industry Research (1975–2010)

Table 1 presents several important insights about the contributions of various nations in the bibliometric examination of the textile industry from 1975 to 2010. The United States emerges as the most prolific country, with 527 documents produced, accounting for 10.81% of the total production during this period, reflecting its prominent position in the field. China is the second most productive country, with 484 documents (9.93%) and an average citation/document of 21.85. According to the total link strength (a value generated by VOSviewer that measures the degree of collaboration of a country), European countries, including Belgium, England, France, Italy, and Spain, have robust collaborative networks. The research originating from these countries also demonstrates a significant research impact, with France leading the way with the highest average citations per document among the top 10 nations.

Table 1. Analysis of prolific countries in global textile industry research (1975–2010).

Country	Documents	Citations	Average Citations/ Document	Total Link Strength
United States	527	19,535	37.07	130
China	484	10,576	21.85	72
India	334	23,369	69.97	38
Turkey	293	9321	31.81	26
England	231	9874	42.74	42
Germany	196	6399	32.65	56
France	169	14,687	86.91	67
Italy	164	9266	56.50	55
Spain	144	9023	62.66	38
Brazil	135	6833	50.61	21

3.1.2. Leading Contributors in Textile Industry Research (1975–2010)

Several significant players have emerged when looking at the most active institutes in the field of textile industry research. With 91 (1.87%) records, Istanbul Technical University is the most productive organization, demonstrating its significant impact. Hong Kong Polytechnic University is in second place, with 72 (1.48%) records, demonstrating its important contribution to the advancement of textile research. With 63 and 59 records, respectively, the University of Zagreb and the Council of Scientific Industrial Research (CSIR) India also exhibit significant activity. Table 2 provides an overview of the prolific institutions in the field of textile industry research during the period of 1975 to 2010.

Table 2. Leading institutions in textile industry research (1975–2010).

Affiliations	Record Count	% of 4873
Istanbul Technical University	91	1.87
Hong Kong Polytechnic University	72	1.48
University of Zagreb	63	1.29
Council of Scientific Industrial Research Csir India	59	1.21
Donghua University	53	1.09
Indian Institute of Technology System Iit System	48	0.99
Centre National de la Recherche Scientifique Cnrs	46	0.94
North Carolina State University	44	0.90
Gh Asachi Technical University	42	0.86
Swiss Federal Institutes of Technology Domain	42	0.86

3.1.3. Exploring Prolific Contributors (1975–2010)

In our bibliometric analysis of the textile industry from 1975 to 2010, we identified the most impactful authors. The most prolific author was Gambiroza-Jukic, M., affiliated with the Croatian Chamber of Economy, who published 33 documents, with an average of 1.06 citations per document. Several authors from Istanbul Technical University in Turkey made notable contributions. Idil Arslan Alaton and Fatos Germirli Babuna each authored 23 papers, with an average of 300 and 363 citations per document, respectively. David B. Thomas, affiliated with the University of Southampton, has the highest average citations per document (35.28), indicating the significant impact of his research. Table 3 lists these prolific contributors, along with their affiliations, countries of origin, the number of papers they have authored, the total citations their work has received, and the average citations per document.

Table 3. Top 10 prolific authors in textile industry research (1975–2010).

Author	Affiliation	Country	Papers	Citations	Average Citations/ Document
Gambiroza-Jukic, M.	Croatian Chamber of Economy	Croatia	33	35	1.06
Alaton, Idil Arslan	Istanbul Technical University	Turkey	23	300	13.04
Fatos Germirli Babuna	Istanbul Technical University	Turkey	23	363	15.78
Orhon, Derin	Istanbul Technical University	Turkey	22	547	24.86
Checkoway, Harvey	University of California San Diego	United States	22	630	28.64
Yi Li	University of Manchester	England	20	42	2.1
Işık Kabdaşlı	Istanbul Technical University	Turkey	18	377	20.94
Karen Wernli	Kaiser Permanence Washington	United States	18	478	26.56
Thomas, David B.	University of Southampton	England	18	635	35.28
Gao, Dao L.	Fudan University	China	18	605	33.61

3.1.4. Highly Cited Articles in Textile Industry Research (1975–2010)

A total of 4873 articles were published in the textile industry during the 1975–2010 period, with the most cited article being "Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative" by Robinson (2001) [47], which was published in *Bioresource Technology* and has been cited 3862 times. The second most cited article is "Non-conventional low-cost adsorbents for dye removal: A review" by Crini (2006) [48], which was also published in *Bioresource Technology* and has been cited 3386 times. The third most cited article is "Adsorption of methylene blue on low-cost adsorbents: A review" by Rafatullah, M et al. (2010) [49], which was published in the *Journal of Hazardous Materials* and has been cited 2256 times. These highly cited articles have had a major impact on textile industry research. Their influence is evident in the high number of times they have been cited by other researchers, which reflects their significant contributions to the field. In Table 4 we present a list of highly cited articles in the field of textile industry research from 1975 to 2010, along with the publishing journal and the number of citations.

Table 4. Bibliometric insights into the evolution of textile industry research (1975–2010).

First Author	Title	Source	IF	C	Ref.
Robinson, T (2001)	Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative	Bioresource Technology	11.4	3862	[47]
Crini, G (2006)	Non-conventional low-cost adsorbents for dye removal: A review	Bioresource Technology	11.4	3386	[48]
Rafatullah, M (2010)	Adsorption of methylene blue on low-cost adsorbents: A review	Journal of Hazardous Materials	13.6	2256	[49]
Houas, A (2001)	Photocatalytic degradation pathway of methylene blue in water	Applied Catalysis B-Environmental	22.1	2229	[50]
Martinez-Huitle, CA (2009)	Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods: A general review	Applied Catalysis B-Environmental	22.1	1925	[51]
John, MJ (2008)	Biofibres and biocomposites	Carbohydrate Polymers	11.2	1464	[52]
Banat, IM (1996)	Microbial decolorisation of textile-dye-containing effluents: A review	Bioresource Technology	11.4	1456	[53]
Pantelopoulos, A (2010)	A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis	Ieee Transactions on Systems Man and Cybernetics Part C-Applications and Reviews	2.171 (2014 last year)	1334	[54]
Lachheb, H (2002)	Photocatalytic degradation of various types of dyes (Alizarin S, Crocein Orange G, Methyl Red, Congo Red, Methylene Blue) in water by UV-irradiated titania	Applied Catalysis B-Environmental	22.1	1324	[55]
Kenawy, ER (2007)	The chemistry and applications of antimicrobial polymers: A state-of-the-art review	Biomacromolecules	6.2	1239	[56]

3.1.5. Co-Authorship Patterns in the Textile Industry (1975–2010)

Figure 4 presents the collaborative networks among researchers from diverse nations. The United States emerged as a prominent hub, with the most documents (527) and a sizable total link strength (140), indicating its significant influence in the network. France demonstrated strong research activity, with 169 documents and an amazing 14,687 total citations. The network exhibited a clustering pattern, with the majority of countries belonging to either the red cluster (16 countries) or the green cluster (12 countries), while the blue cluster encompassed fewer countries (9). The red cluster primarily comprises European countries, with a notable concentration of European nations on the left side of the network map. This spatial structure strongly suggests greater collaboration between these European nations.

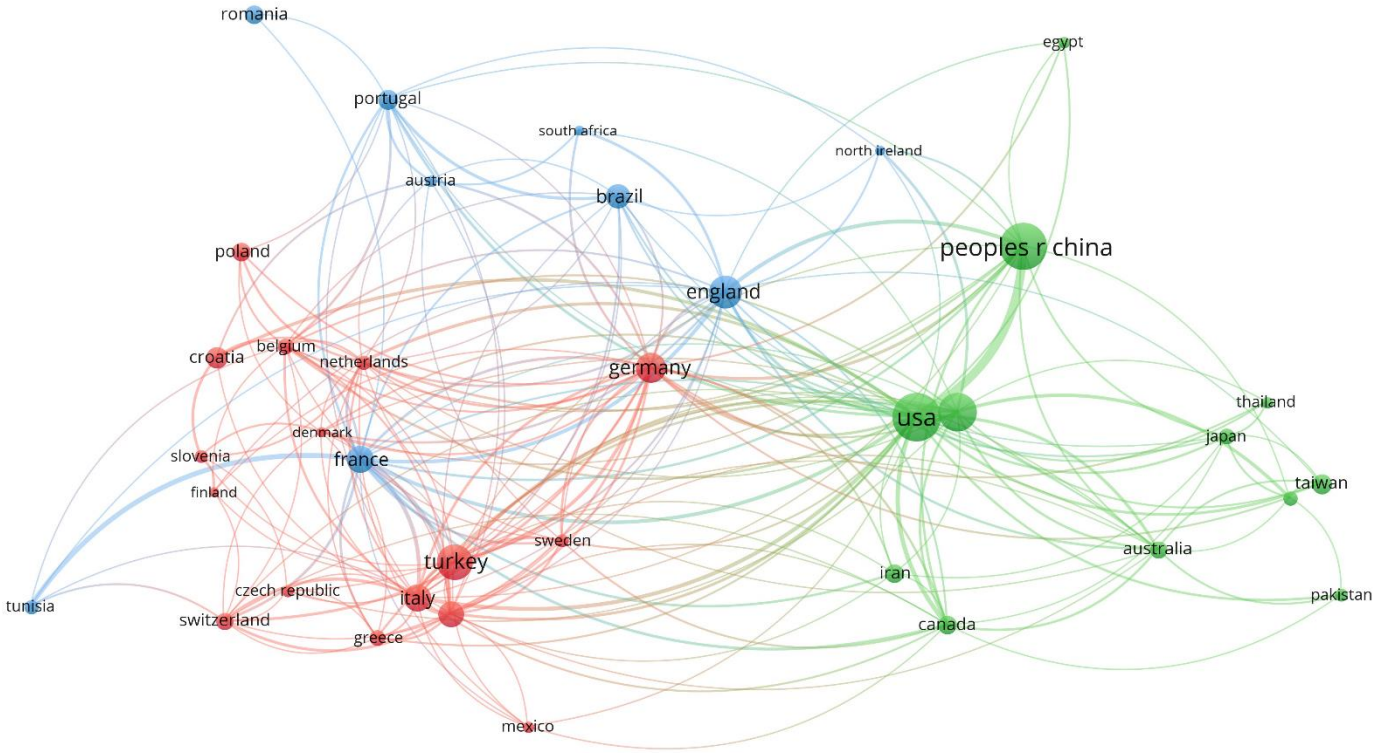


Figure 4. Country co-authorship network and clustering patterns in textile industry research (1975–2010).

3.1.6. Citation Map of Sources (1975–2010)

Figure 5 illustrates a citation network map featuring scholarly sources systematically grouped into four distinct clusters. Specifically, there is a cluster denoted in red, encompassing ten journals, a green cluster comprising six journals, a blue cluster containing four journals, and a yellow cluster housing three journals. Notably, the green and blue clusters emphasize the environmental ramifications of the industry under scrutiny, while the red and yellow clusters center their focus on the industrial aspects of the textile sector. Worth mentioning is that although "Tekstil" ranks as the most influential journal within this timeframe, journals such as the "Journal of Chemical Technology and Biotechnology," "Desalination," "Journal of Hazardous Materials," and "Environmental Technology" appear to wield considerably more influence in this particular domain. This revised text is well-suited for publication in a scientific journal.

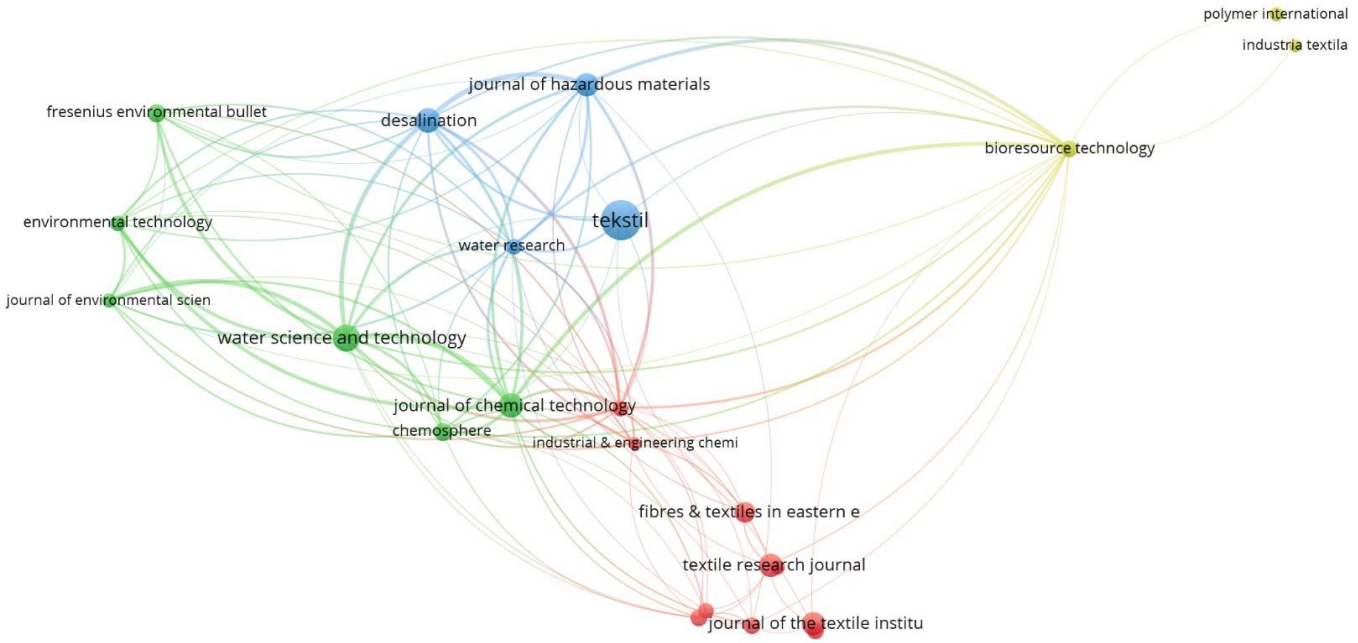


Figure 5. Citation network of scholarly sources in the textile industry between 1975 and 2010.

3.1.7. A Visual Exploration of the Most Influential Terms in the Textile Industry (1975–2010)

Figure 6 shows a term co-occurrence network map of the most influential terms in this field, with at least 50 occurrences. The terms "adsorption", "aqueous-solutions", "dyes", "kinetics", and "oxidation", all of which are intimately linked to procedures involving the removal and treatment of dyes and pollutants in aqueous environments, are included in the red cluster. The green cluster, on the other hand, is focused on coloration and wastewater treatment in the textile sector. This is evident from the keywords that are associated with this cluster, such as "color", "color removal", "dye", "effluents", and "wastewater". The blue cluster emphasizes biodegradation, enzyme-mediated processes, and purification methods for textile dyes through the predominance of phrases like "azo dyes", "decolorisation", "enzymes", and "laccase". Last but not least, the yellow cluster includes terms like "textile", "textile industry", "cotton", and "performance", indicating that it places a focus on a variety of aspects of textile production, including industry performance and the materials used.

3.1.8. Key Terms and Emerging Patterns in the Textile Industry (1975–2010)

Figure 7 presents the node map of the most influential keywords in textile industry research. The industry's commitment to tackling environmental issues related to dyeing procedures is demonstrated by the term "color removal" (166.29 average citations, 62 occurrences). Researchers were interested in "textile wastewater" (223.65 average citations, 103 occurrences), demonstrating the growing importance of sustainable wastewater management. The term "textile dyes" (149.79 average citations, 58 occurrences) demonstrated a steadfast interest in dye components and uses. The startlingly high average number of citations (235.36, 50 occurrences) for "white-rot fungi" highlighted its critical function in biodegradation and environmental remedies. In contrast, "cotton" (24.65 average citations, 93 occurrences) and "textile industry" (29.35 average citations, 282 occurrences) occupied a less central position in recent research inquiries, potentially indicating shifting scholarly priorities.

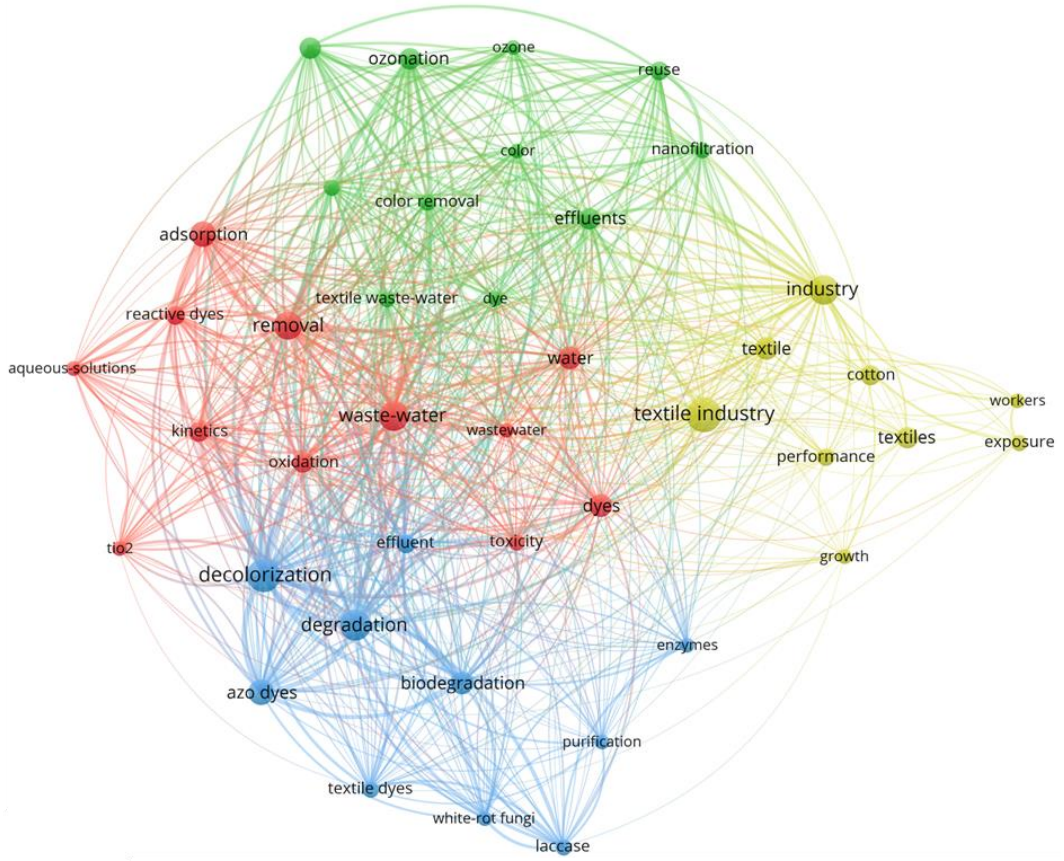


Figure 6. Textile industry term co-occurrence network map (1975–2010).

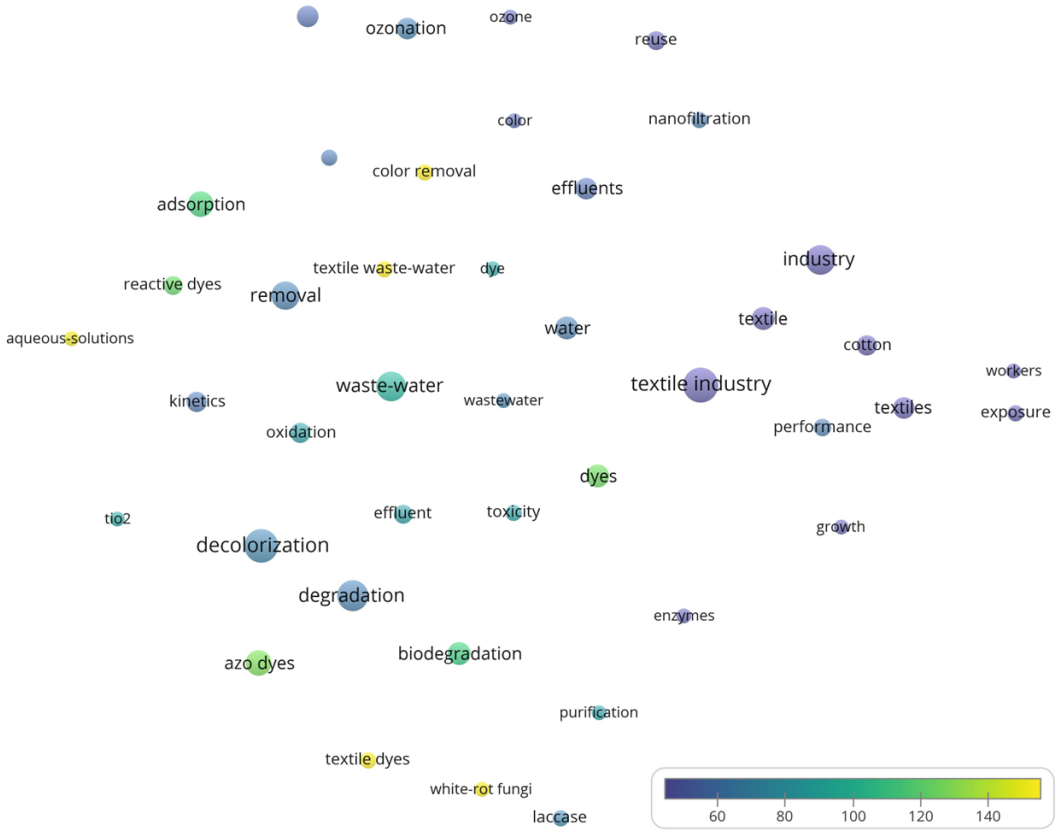


Figure 7. Influential keywords in textile industry research (1975–2010).

3.2. Period 2011–2023

3.2.1. Top Contributors in Global Textile Industry Research (2011–2023)

Table 5 provides valuable insights into the contributions of various countries in the field of global textile industry research for the period spanning from 2011 to 2023. China emerges as the most prolific country during this period, producing 2478 documents, which account for 18.44% of the total production, reflecting China's substantial role in textile research. India closely follows China in productivity, with 2197 (16.35%) documents and an average citation per document of 21.71, showcasing the quality of research output from India. The United States, though producing fewer documents, maintains a strong research impact, with an average citation per document of 25.06, underlining its continued prominence in the textile industry research landscape. The data provided are extremely relevant to policymakers, practitioners, and researchers because they may inform the rise of powerful nations and influence partnerships, collaborations, and technology transfer.

Table 5. Analysis of prolific countries in global textile industry research (2011–2023).

Country	Documents	Citations	Average Citations/Document	Total Link Strength
China	2478	44,403	17.92	1014
India	2197	47,696	21.71	805
United States	975	24,437	25.06	728
Turkey	723	9111	12.60	168
Brazil	679	11,418	16.82	236
Pakistan	676	10,910	16.14	549
England	553	12,767	23.09	602
Iran	495	11,492	23.22	184
Germany	446	8431	18.90	327
Spain	432	12,309	28.49	317

3.2.2. Leading Contributors in Textile Industry Research (2011–2023)

Insightful information on the top organizations conducting research on the textile sector from 2011 to 2023 is provided in Table 6. During this time, these institutions have significantly contributed to the development of textile research. With 262 records, the Indian Institute of Technology (IIT) System stands out as the most productive institution, highlighting its ongoing and significant influence on textile research. With 245 records, the Egyptian Knowledge Bank (EKB) stands out as the second most active institution, highlighting its expanding significance in the field of textile research worldwide. EKB's contribution emphasizes the value of cross-border cooperation in the industry. Policymakers can leverage these results to identify institutions with a strong research footprint in the textile sector, and can allocate funding. The data can help universities and researchers identify and build prospective collaboration networks within and among academic institutions and the research community.

Table 6. Leading institutions in textile industry research (2011–2023).

Affiliations	Record Count	% of 4873
Indian Institute of Technology System Iit System	262	1.95
Egyptian Knowledge Bank Ekb	245	1.82
Donghua University	212	1.58
National Institute of Technology Nit System	197	1.47
Council Of Scientific Industrial Research Csir India	147	1.09
Chinese Academy of Sciences	144	1.07
Centre National de la Recherche Scientifique Cnrs	126	0.94
Hong Kong Polytechnic University	125	0.93
University of Agriculture Faisalabad	116	0.86
Islamic Azad University	111	0.83

3.2.3. Exploring Prolific Contributors (2011–2023)

We move our focus to the years between 2011 and 2023 in our ongoing bibliometric examination of the textile sector in order to pinpoint the writers who had the most influence during this time. Wang, Laili from the Xi'an Jiaotong University School of Electrical Engineering in China emerges as the most prolific author during this period, with 32 papers and an average of 9.91 citations/document. Govindwar, Sanjay P. from Shivaji University in India is the second most prolific author of the period, with 27 papers. His work has received a substantial number of citations, with an impressive average citation per document of 80.44, reflecting his research's high impact and significance. The top 10 authors are listed in Table 7, along with their affiliations, places of origin, the number of papers they have written, the total number of citations their work has obtained, and the average citations per document.

Table 7. Top 10 prolific authors in textile industry research (2011–2023).

Author	Affiliation	Country	Papers	Citations	Average Citations/ Document
Wang, Laili	Xi'an Jiaotong University School of Electrical Engineering	China	32	317	9.91
Govindwar, Sanjay P.	Shivaji University	India	27	2172	80.44
Muhammad, Bilal	Huaiyin Institute of Technology	China	23	1114	48.43
H.M.N. Iqbal	Princess Nourah Bint Abdulrahman University	Saudi Arabia	22	1178	53.55
Thomas Gries	RWTH Aachen University	Germany	20	31	1.55
Cristi Marcel Spulbar	University of Craiova	Romania	19	24	1.26
Ramona Birau	Constantin Brancusi University	Romania	17	24	1.41
Xuemei Ding	Donghua University	China	16	326	20.38
Haq Nawaz Bhatti	University of Agriculture Faisalabad	Pakistan	16	366	22.88
Muhammad Asgher	University of Agriculture Faisalabad	Pakistan	16	1079	67.44

3.2.4. Highly Cited Articles in Textile Industry Research (2011–2023)

A total of 13,436 articles were published in the textile industry during the 2011–2023 period, with the most cited article being "Antibacterial properties of nanoparticles" by Hajipour, M.J. (2012) [57], which was published in *Trends in Biotechnology* and has been cited 1714 times. The second most cited article is "Zinc Oxide-From Synthesis to Application: A Review" by Kolodziejczak-Radzimska, A. (2014) [58], which was published in *Materials* and has been cited 1582 times. These articles are useful to practitioners since they provide a comprehensive account of the most current accomplishments in textile industry research. This information enables practitioners to improve their goods and processes, investigate new technologies, and maintain a competitive edge in a rapidly changing field. These resources also serve to highlight current trends in the scientific community, allowing researchers to better align their studies. In Table 8, we present a list of highly cited articles in the field of textile industry research, along with the publishing journal and the number of citations.

Table 8. Bibliometric insights into the evolution of textile industry research (2011–2023).

First Author	Title	Source	IF	C	Ref.
Hajipour, MJ (2012)	Antibacterial properties of nanoparticles	Trends in Biotechnology	17.3	1714	[57]
Kolodziejczak-Radzimska, A (2014)	Zinc Oxide-From Synthesis to Application: A Review	Materials	3.4	1582	[58]
Lee, KM (2016)	Recent developments of zinc oxide based photocatalyst in water treatment technology: A review	Water Research	12.8	1486	[59]
Verma, AK (2012)	A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters	Journal of Environmental Management	8.7	1287	[60]
Pielichowska, K (2014)	Phase change materials for thermal energy storage	Progress in Materials Science	37.4	1236	[61]
Martinez-Huitle, CA (2015)	Single and Coupled Electrochemical Processes and Reactors for the Abatement of Organic Water Pollutants: A Critical Review	Chemical Reviews	62.1	1120	[62]
Holkar, CR (2016)	A critical review on textile wastewater treatments: Possible approaches	Journal of Environmental Management	8.7	1103	[63]
Saratale, RG (2011)	Bacterial decolorisation and degradation of azo dyes: A review	Journal of the Taiwan Institute of Chemical Engineers	5.7	982	[64]
Kamal, MS; (2016)	Catalytic oxidation of volatile organic compounds (VOCs)—A review	Atmospheric Environment	5	957	[65]
Su, B (2016)	Bioinspired Interfaces with Superwettability: From Materials to Chemistry	Journal of the American Chemical Society	15	848	[66]

3.2.5. Co-Authorship Patterns in the Textile Industry (2011–2023)

Figure 8 presents the collaborative networks among researchers from various countries in the period 2011–2023 in the field of textiles. The map encompasses all countries with

at least 50 published articles. The countries have been grouped into five distinct clusters: red, yellow, green, blue, and purple. The red cluster is the largest, comprising a total of 20 countries, with the majority being European nations. The green cluster consists of 12 countries, including India and China, the most prolific countries during this period. Within the green cluster, it is noticeable that the majority of countries are from Asia. The blue cluster includes nine countries from Latin America and Europe, highlighting the international nature of research in this field. The yellow cluster encompasses eight countries, primarily consisting of North African and Middle Eastern nations. The purple cluster comprises seven countries, and there does not seem to be a discernible geographical pattern. A noteworthy aspect for consideration is the central positioning of China, India, the United States, and England on the map. This prominence is a result of these countries engaging in extensive collaborations with other nations, effectively showcasing the truly global nature of research within this domain.

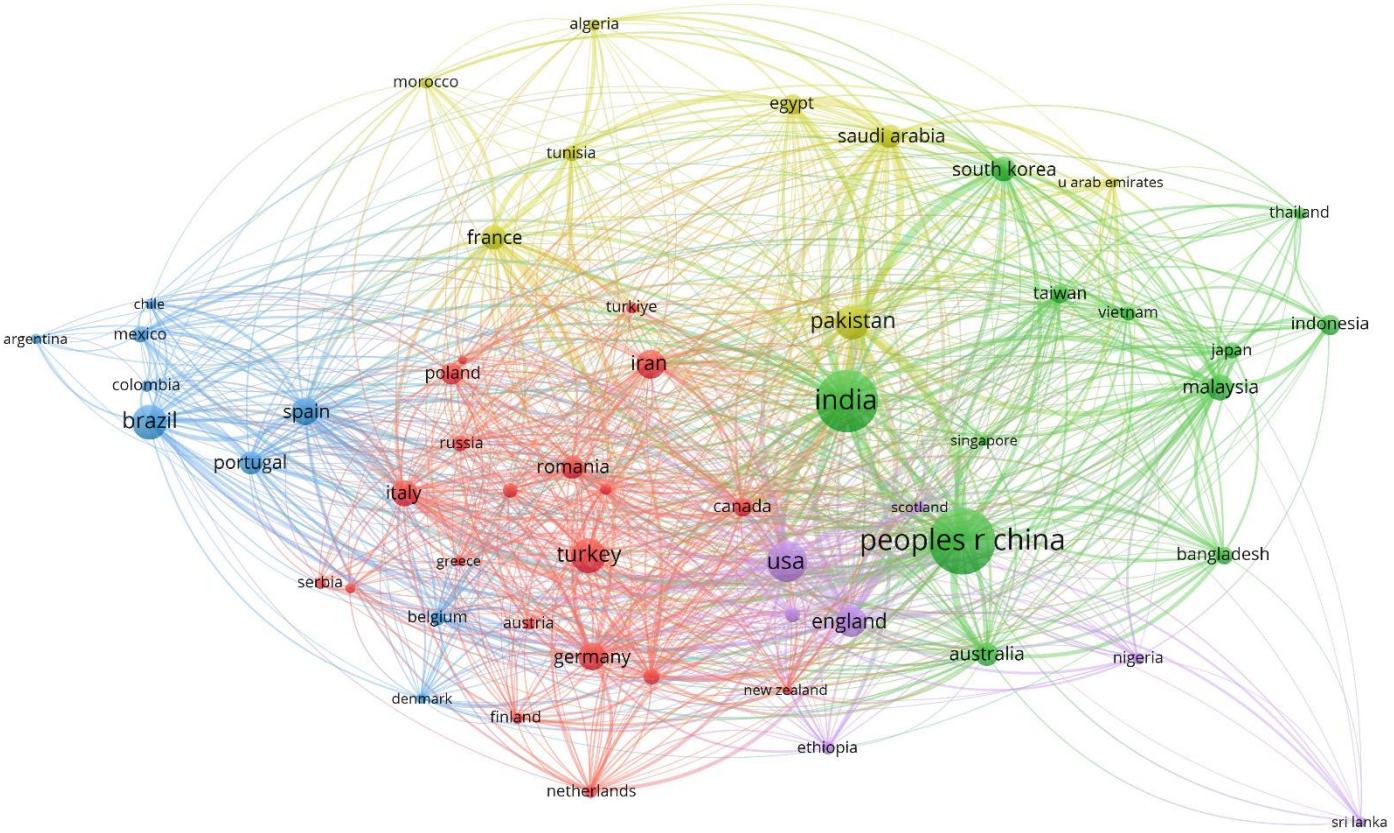


Figure 8. Country co-authorship network and clustering patterns in textile industry research (2011–2023).

3.2.6. Citation Map of Sources (2011–2023)

Figure 9 represents the citation network map of journals. During the period 2011–2023, journals can be categorized into two distinct clusters, namely the red cluster, which includes 17 journals, and the green cluster, which comprises 15 journals. It is worth noting that this analysis includes journals that have published a minimum of 50 articles during this period. As the foundation of the textile industry, textiles, fibers, and polymers appear to be the primary emphasis of the red cluster. In contrast, the green cluster has journals in the fields of environmental science, chemistry, and chemical engineering focused on uncovering the textile industry's environmental effects.

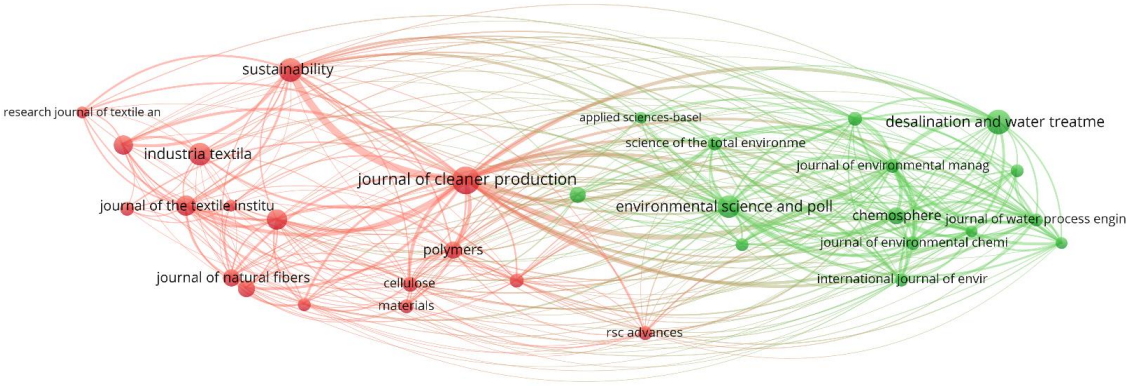


Figure 9. Citation network of scholarly sources in the textile industry between 2011 and 2023.

3.2.7. A Visual Exploration of The Most Influential Terms in the Textile Industry (2011–2023)

Figure 10 presents a term co-occurrence network map of prominent terms in the field, each with at least 150 occurrences. Within this network, four distinct clusters emerge. The blue cluster, which includes 15 terms and is characterized by keywords such as "activated carbon", "adsorption", and "removal", underscores research on adsorption processes, particularly involving activated carbon, in water treatment and purification. This area of study is of growing importance and is rapidly evolving within the context of water treatment and purification. The green cluster includes 20 keywords, and it focuses on "azo dyes", "decolorization", and "wastewater", highlighting studies on the removal and treatment of azo dyes in textile effluents. Azo dyes, which are used in the textile industry, are under the category of synthetic dyes. Nonetheless, these dyes have hazardous characteristics and a sluggish breakdown rate. As a result, when dumped into wastewater they constitute a significant environmental risk. The yellow cluster includes 14 terms like "nanoparticles", "photocatalysis", and "silver nanoparticles", emphasizing research in the domain of nanotechnology, specifically in the context of textile wastewater treatment and catalytic degradation. Finally, the red cluster, the largest of all, encompasses keywords such as "textile", "industry", "sustainability", and "waste", signifying a wide spectrum of research in the textile industry, including sustainability practices, waste management, and industry innovations, thus suggesting the movement towards a more sustainable future, driven by a strong desire to address the environmental challenges linked to textile production.

3.2.8. Key Terms and Emerging Patterns in the Textile Industry (2011–2023)

Figure 11 depicts the node map of the most influential keywords in textile industry research. The industry's commitment to addressing environmental issues is represented by the terms "removal" (averaging 18.16 citations with 1192 occurrences) and "adsorption" (17.99, 1060). Researchers have shown a keen interest in "textile waste-water" (39.17, 163) and "waste water treatment" (33.63, 162), underscoring the increasing importance of sustainable wastewater management. Other terms that have shown a high average number of citations are represented by "azo-dye" (38.50, 309), "reactive dyes" (38.93, 189), "silver nanoparticles" (46.98, 187), and "synthetic dyes" (54.04, 166). These words have garnered significant attention and citations in textile industry research due to their critical roles and relevance within the field. Given the focus on wastewater treatment, dyes, and environmental concerns, it is likely that researchers in the textile industry are collaborating with experts in fields such as chemistry, environmental science, and materials science. This interdisciplinary approach is crucial for finding holistic and effective solutions to the industry's sustainability challenges. Overall, these data reflect a positive trend in the textile industry towards addressing environmental issues and embracing sustainable practices. It also highlights the importance of ongoing research and innovation in developing more eco-friendly and responsible methods for textile production and wastewater management.

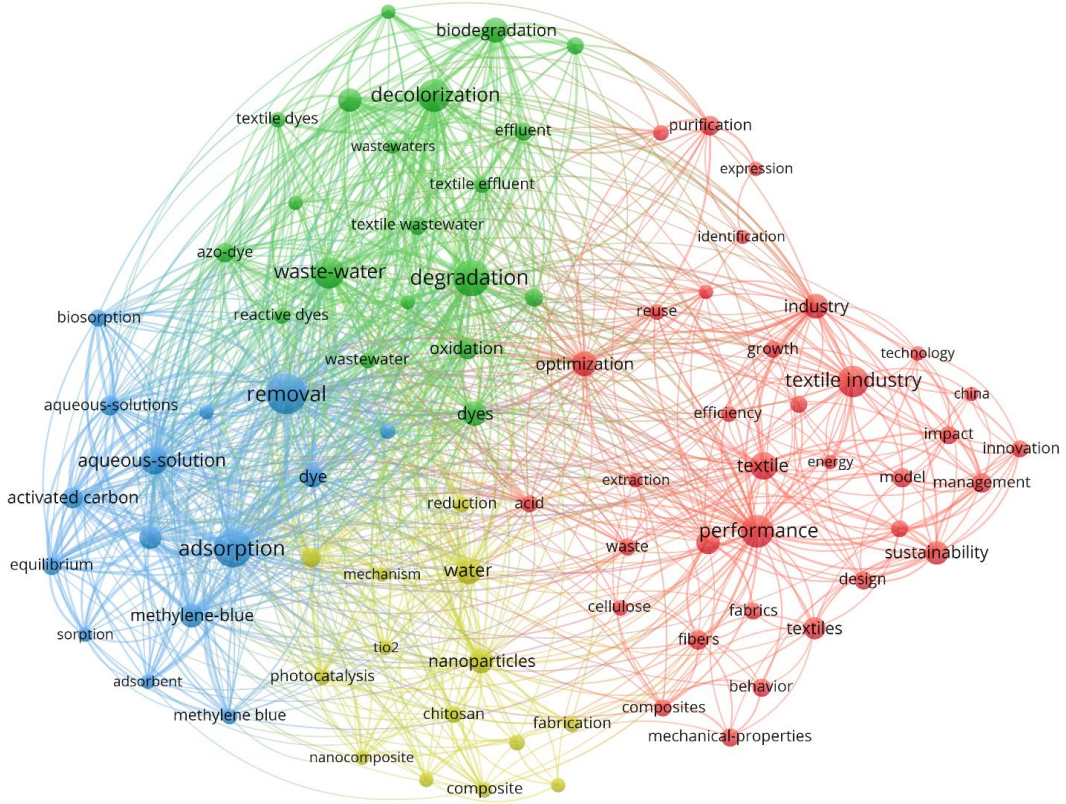


Figure 10. Textile industry term co-occurrence network map (2011–2023).

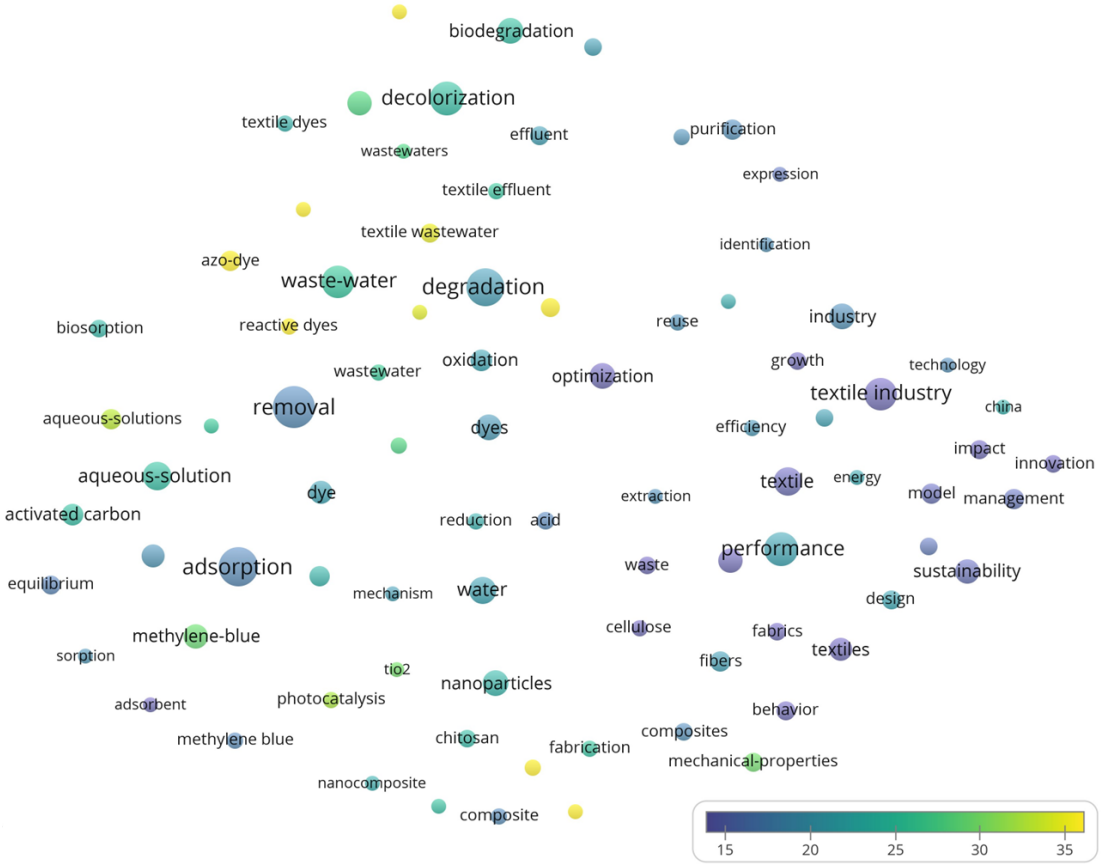


Figure 11. Influential keywords in textile industry research (2011–2023).

4. Discussion

The United States emerged as the most prolific country, producing 527 documents, showcasing its significant contributions to textile research during the first period. China followed closely as the second most productive nation, with 484 documents, highlighting its growing presence in the field. European countries, such as Belgium, England, France, Italy, and Spain, had a strong presence in the top 10 most productive countries, with France leading in average citations per document. China solidified its position as the global leader in textile industry research in the second period, contributing a substantial 2478 papers, emphasizing its pivotal role in advancing textile science. Over the decades, there has been a noticeable shift in the global textile research landscape, with China and India significantly increasing their contributions.

Emerging scholars can benefit from the analysis of prolific writers and important papers in two different ways. First, it might give authors knowledge of the influential authors and works that have shaped the discipline. Second, it can link them up with a network of specialists. Additionally, through a detailed examination of collaboration network maps among nations, prospective authors can easily identify potential collaborators, thereby advancing research in this field. By comparing the two collaboration network maps, one can discern a shift towards more diverse collaborations, which is advantageous for future researchers in this domain.

Collaboration networks are essential to the advancement of circular economy implementation in the textile and apparel industries. This study sought to present the collaborative landscape by identifying systems of researchers, institutions, and organizations. Knowing the patterns of collaboration may foster partnerships and improve the exchange of knowledge among stakeholders, ultimately promoting the industry's sustainable development. Moreover, the bibliometric examination showed the most prolific countries contributing to research on the implementation of the circular economy in the textile and apparel industries. By analyzing the geographical spread of research output, one can acquire valuable insights. Areas that have made significant contributions can serve as models for other regions, while areas with less research activity might benefit from increased attention and support.

Through a detailed exploration of influential terms and keywords, as well as the visualization of term co-occurrence network maps, we have unveiled significant shifts and emerging patterns in textile research. Initially, the textile industry was heavily invested in environmental issues, particularly the removal and treatment of dyes and pollutants from water. Researchers concentrated on "color removal" and "textile wastewater," demonstrating the industry's increased commitment to environmentally friendly wastewater treatment. "Textile dyes" and "white-rot fungi" became prominent research topics as well. Notably, the terms "cotton" and "textile industry" were referenced less frequently, indicating that scholarly priorities were shifting. The textile industry remains committed to environmental sustainability. Researchers continue to focus on dyeing processes that are less harmful to the environment. This is evident in the frequent use of terms such as "removal" and "adsorption" in the literature. These terms refer to methods of removing and treating dyes from wastewater. Researchers are working to develop eco-friendly and efficient methods for doing this. Nanotechnology is increasingly being used in the textile sector. This may be seen in the growing use of terminology like "nanoparticles," "photocatalysis," and "silver nanoparticles" in textile research. This shows that the textile sector is getting more interested in using nanomaterials and catalytic techniques to clean textile effluent and break down contaminants in the environment.

The data provided can be utilized by policymakers, industry leaders, and researchers to formulate strategies and allocate resources effectively. In addition to a country-level evaluation, this study identified the prominent journals publishing research on the textile and apparel industries. For academics and industry professionals seeking credible venues to disseminate their work and keep apprised of the latest developments, journal analysis is indispensable. By examining the characteristics and influence of these journals, this analysis

will increase the visibility and dissemination of research pertaining to the implementation of a circular economy in the textile and apparel industries.

The selection of influential articles based on citation analysis was another crucial aspect of this bibliometric analysis. These prolific articles are fundamental publications that contributed to the development of the field. The analysis of their contents can yield valuable insights, methodologies, and approaches that have proven effective in the textile and apparel industries.

Our findings are in accordance with the observations of Forno et al. about the importance and use of digital technologies in the textile industry, but we found an increasing scientific interest in sustainable development and nanoparticle use [67]. The increasing use of nanoparticles for different purposes in the textile industry and the evaluation of different types of dyes for wastewater reduction are also supported by the results of other bibliometric analyses in the textile field [68,69].

The results for the most prolific countries (e.g., the United States and China) doing sustained research in the textile industry are identical in type of analysis to those in a similar paper by Halepoto et al., which specifically evaluated the use of artificial intelligence in the textile industry [70]. Moreover, textile wastewater and the process of adsorption are notably prevalent keywords, indicating the primary focus of current research in this domain, with a noticeable increase in attention in recent years. These findings are in alignment with the observations made by Kasavan et al. [71].

Bibliometric analyses come with several notable advantages, and perhaps one of the most significant merits is their inherent neutrality. This neutrality ensures that other researchers can replicate the results using the same methods without being influenced by the personal biases of the original author. This quality makes bibliometric analyses a valuable tool for evaluating research quality and identifying emerging trends. Furthermore, bibliometric analyses excel in the systematic examination of extensive textual bodies, providing a comprehensive overview of the subject being studied.

The bibliometric analysis centered on the implementation of circular economy principles within the textile industry provides a wealth of valuable insights to a diverse array of stakeholders, with the fundamental contribution relying on the fact that it is the first to use this algorithm in this targeted subfield. Researchers and academics stand to benefit by obtaining a comprehensive grasp of the research landscape, pinpointing influential authors, and discerning emerging trends within this field. For industry professionals, it serves as an invaluable resource for staying abreast of the latest developments and sustainable practices within the textile and apparel sector. Policymakers and governmental bodies can harness this analysis to inform policy decisions concerning sustainability, waste reduction, and resource management. Educational institutions and students can utilize this resource to delve into fundamental concepts and reputable academic institutions, while international organizations and non-governmental organizations can leverage it to bolster sustainable initiatives and advocacy endeavors. Furthermore, investors and entrepreneurs can employ this analysis to identify nascent technologies and promising startups operating within the textile industry, facilitating informed investment choices and sustainable business strategies. In essence, the present bibliometric analysis plays a pivotal role in fostering evidence-based decision-making, collaboration, and sustainability within the textile sector.

5. Conclusions

The textile and apparel industries can transition towards a more sustainable and circular production system through the implementation of waste reduction strategies at every stage of production and digital technologies. This comprehensive approach, aligned with circular economy principles, has the potential to present stakeholders with opportunities to substantially reduce textile waste production and create an industry with a greater concern for the environment.

The present bibliometric analysis is essential to comprehending the research landscape and trends in the textile and apparel industry's implementation of circular economy

elements. It offers useful knowledge into publication structures, citation networks, and collaboration patterns, guiding decision-making based on evidence and identifying research gaps. By utilizing bibliometric analysis, policymakers, researchers, academics, and students are able to make informed decisions, promote the dissemination of knowledge, set research objectives and themes related to collaborative networks and journals publishing in the field by reference to valuable validated papers and a high number of citations in valuable journals, and promote sustainable practices in the textile and apparel industries. Moreover, the practical implications of the present analysis may also lead to the possibility of forming collaborative networks with other important stakeholders in the field, information that can be obtained from the present evaluation. This helps achieve sustainability objectives and reduce environmental impacts.

Research Limitations and Future Research Directions

The limitations of the present article stem primarily from the method of analysis used. When evaluating a large number of articles, such as the 18,309 in our study, there is a possibility of false-positive articles that may not be directly related to the research topic and are inadvertently included in the dataset. Another limitation that needs to be considered is that although the WoS database is comprehensive, it does not encompass all research within the field. Some relevant research may not be indexed in this database, including data from very old publications. Moreover, other drawbacks refer to language and geographic biases, which omit the inclusion of publications written in other languages or in other regions. Some very valuable but very recent publications have a significantly lower number of citations due to the date of publication, so they are not yet included in the top of most relevant papers in the field. The number of citations a paper receives should not be the sole indicator of its quality or scientific rigor, as highly cited papers may not always possess the highest level of scientific validity.

Future research directions in this field are poised to significantly impact sustainability within the textile and apparel industries. One crucial avenue for exploration is the practical application of circular economy principles, with a particular focus on assessing their cost-effectiveness, environmental implications, and emerging trends. Additionally, it is imperative to investigate regional disparities in the adoption of circular economy strategies within the textile sector. Analyzing how different geographic regions address unique challenges and opportunities related to sustainability will uncover valuable insights and best practices. These findings can be crucial for tailoring circular strategies to specific contexts and overcoming regional barriers. Lastly, staying abreast of emerging trends and technologies, such as innovative materials, manufacturing methods, and digital solutions, is vital. Employing bibliometric analysis can guide researchers in identifying influential publications, authors, and journals in this dynamic field, facilitating informed decisions, and fostering sustainable practices across the textile and apparel industries.

Analyzing the progression of this field, it can be objectively stated that sustainability has played and continues to play a significant role in textile research. This shifting landscape of prolific authors, collaboration networks, and key terms reflects the field's ability to adapt, embracing interdisciplinary approaches and international cooperation, hinting at promising future advancements. These findings offer valuable insights for professionals and researchers seeking to comprehend the ever-evolving textile research field.

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