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A Two-Decade (2004-2025) Bibliometric Analysis of Textile Wastewater Reuse: Trends, Hotspots, and Future Direction

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Abstract

Introduction: The reuse of textile wastewater has become a growing area of interest worldwide as it plays an important role in sustainable water management and environmental conservation. Even though individual research studies are plentiful, there have been few comprehensive investigations of global research trends on a long-term scale. This research aimed to describe the bibliometric analysis of research on the reuse of textile wastewater from 2004 to 2025.

Methods: The Web of Science search yielded 1324 peer-reviewed articles on the topic of textile wastewater. Mapping was done using VOSviewer, Gephi, Pajek, and BibExcel to analyze co-authorship networks, keyword co-occurrence, citation patterns, and institutional contributions. The inclusion criteria, language distribution, and publication types were well described, and a PRISMA flow diagram was used to ensure methodological transparency.

Results: The total number of articles under analysis, 1324 (98.95%) were published in English. The highest number of publications were recorded in 2024 (more than 160). Most were contributed by China (62%), followed by India (10.61%), and Turkey (9.3%). Environmental sciences (20.31%) and chemical engineering (17.14%) accounted for the largest shares of published articles. The total number of citations of all the articles included was 51,868, with a mean number of citations per article of 38.77 and a mean H-index of 103.

Conclusion: The paper provides a new synthesis of the existing literature on textile wastewater reuse and offers valuable insights into publication trends, citation patterns, and the evolution of themes.

Keywords: Wastewater, Bibliometrics, Textiles, Water reuse

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Introduction

The world is facing the mounting challenge of water scarcity, exacerbated by rapid urbanization, industrialization, and population growth. The textile industry is considered one of the most water-consuming and water-polluting among industrial sectors. The manufacturing operations in textile industries produce massive amounts of wastewater contaminated with multi-ingredient mixtures of dyes, chemicals, salts, and micro-pollutants, most of which are non-biodegradable and pose serious environmental and health threats. Recent studies show the textile industry as a significant source of water pollution, accounting for about 20 percent of global industrial discharges. There is an urgent need to implement sustainable water management practices because all aspects of the ecosystem are severely degraded by industrialization and urbanization (1).

The textile industry, valued at USD 2.0 trillion, employs 450 million people worldwide (2,3). It contributes significantly to the global environmental footprint at every stage of its operations. For instance, 100–200 liters of water is required for the production of 1 kg of textile product, with 55% of the water discharged as wastewater (4,5). It is essential for the industry to properly manage its water resources and ensure that wastewater is treated and disposed of appropriately. The basic, secondary, and tertiary methods involved in treatment are all considered conventional technologies (6,7). The treatment methods have also advanced tremendously in the past twenty years through membrane filtration, advanced oxidation processes, biological treatment, and integrated hybrid systems. Even though there is a substantial amount of research on treating textile effluent with kenaf fibers, there is still a need for a systematic understanding of global trends, influential factors, and thematic development of textile wastewater reuse methods. Lovino et al. reported that using UV light in combination with other advanced treatment technologies is a more environmentally benign method for removing Ibuprofen from synthetic water streams than alternative treatments (8,9). An aqueous mixture of dye and Na_2SO_4 was successfully separated by ultrafiltration (UF), yielding a desalination efficiency of 98% and a dye recovery of>97%. Consumption of water, treatment of wastewater, and the potential for effluent reuse have all become essential components of environmentally responsible production and management (10-12). Therefore, it is extremely difficult to find a technology that is both successful and efficient in treating and recycling wastewater from the textile sector for reuse.

Ultrafiltration (UF), reverse osmosis (RO), and nanofiltration (NF) are used extensively for the treatment of chemicals and reusing water to meet environmental guidelines (13,14). Wastewater treatment options such as artificial wetlands, activated carbon, and ion exchange are among the options for reusing textile wastewater (15,16). Although experiments have been conducted using wastewater treatment technologies, there is little evidence, from bibliometric perspective, of their use in textile wastewater reuse. The majority of current reviews consist of written reviews that do not involve an in-depth analysis of networks and trends generated by advanced bibliometric software.

The present study conducts an in-depth bibliographic review of global research on textile wastewater reuse from 2004–2025. Using a collection of 1324 peer-reviewed articles acquired from the Web of Science, this paper employs a mixed-method approach using VOSviewer, Gephi, Pajek, and Bibexcel to examine trends in publications, research collaboration networks, and emerging thematic domains. This manuscript presents information that explicitly depicts the research progress in the domain of textile wastewater treatment with the aim of providing a framework to help researchers and practitioners identify key contributions and trends across authors, journals, countries, institutions, references, and research topics.

Materials and Methods

Web of Science was used to extract data, with the selection narrowed to English-language journal articles. Bibliometric applications VOSviewer, Gephi, Pajek, and Bibexcel were used to gain insights into publication trends, co-authorship, keyword co-occurrence, and citations. The search term "Textile Wastewater Reuse" was used. For data cleaning, the inclusion (article & review article) and exclusion (proceeding paper, early access) criteria were applied, resulting in the removal of 19 articles. Data were collected up to August 2025. All steps are represented in the PRISMA flow diagram in Figure 1.

Using this method, research hotspots and trends in different countries were identified (17). The retrieved publications were analyzed using bibliometric methods. The data were analyzed by using scientific mapping analysis. VOSviewer, Bibexcel, Pajek, and Gephi software were used for visualization of the processed data. The maps produced by VOSviewer and Pajek software were used to analyze co-authorship, co-occurrence, bibliographic coupling, and citations (18,19). These methods were used to conduct a literature review that included meta-analysis and a qualitative analysis of research themes, specifically examining the interrelationships among individual studies. Figure 2 shows the methodology used for analyzing the data using bibliometrics: publication, authors, document type, source, author's affiliation, keywords, and country.

Performance analysis and scientific mapping are the main procedures in bibliometrics. Performance analysis

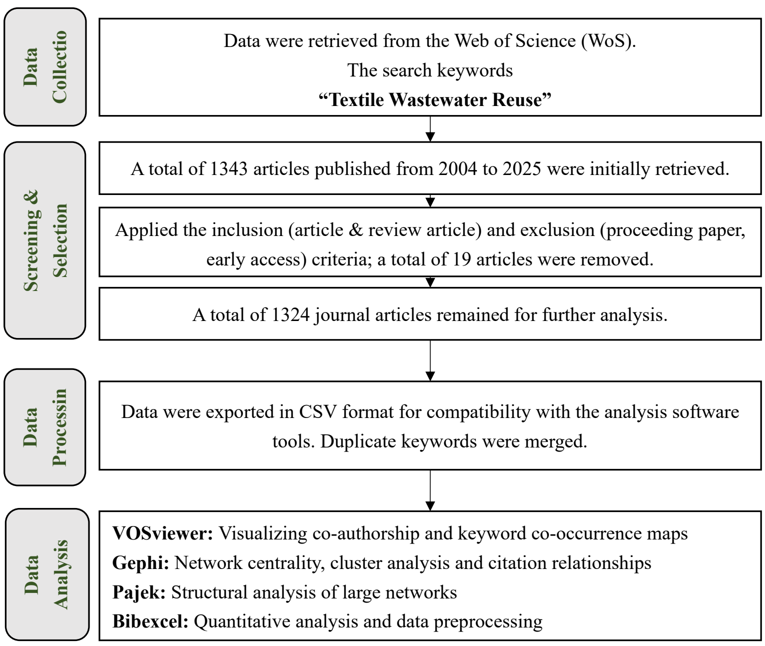

Figure 1. PRISMA flow diagram

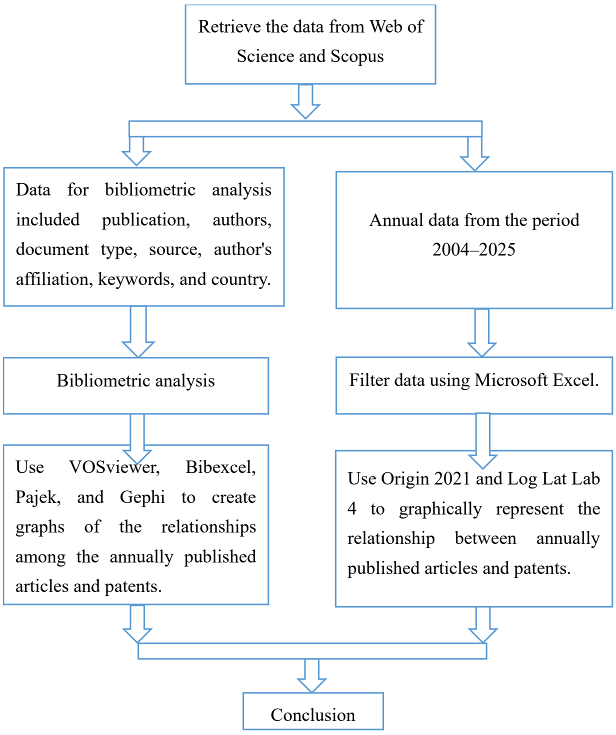

Figure 2. Methodology overview

aims to evaluate researchers, authors, departments, and universities concerning their activities. Scientific mapping aims to represent the structure of a research field. The main data for bibliometric analysis were publication, authors, document type, source, author's affiliation, keywords, and country.

Results

Article characteristic

Using the keyword "Textile Wastewater Reuse" to search the Web of Science database, a total of 1324 articles were retrieved and analyzed. This analysis confirmed that most of the databases are in English and that journal articles are the most common document type for scientific exchange. The number of publications shows a significant increase from 2004 to 2025, as illustrated in Figure 3.

More than 160 articles were published in 2024, the year with the highest publication count. The annual published articles showed a progressive increase, which is an indication of stable growth and improving communication in the research field. The cumulative percentage represents the total number of articles published up to a given year. Fewer articles were published in 2025, because the data were collected only up to August 2025.

Contribution of different countries

The geographic distribution of publications revealed the strong predominance of China with 274 (24.62%), followed by India with 118 (10.61%), Turkey with 104 (9.3%), Spain with 82 (7.37%), Brazil with 81 (7.28%), USA with 52 (4.67%), Italy with 51 (4.58%), Pakistan with 47 (4.22%), Iran with 43 (3.86%), and Saudi with Arabia 41 (3.68%). These top 10 countries saw a significant increase

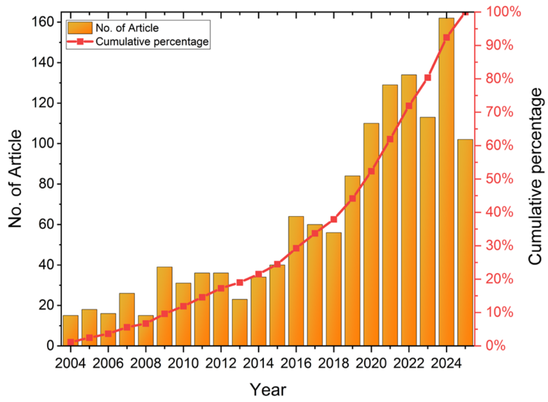

Figure 3. Annual publications with cumulative percentage

in wastewater reuse. Figure 4 shows the contributions of various countries in wastewater reuse, with larger circles indicating greater contributions through more publications and smaller circles representing fewer publications. In this network analysis, the size of each node is proportional to the publication volume from the corresponding country, while the edge weight signifies the intensity of inter-country collaboration.

Citation network analysis

Citation network analysis is a quantitative technique applied to study the intellectual organization of a scientific subdiscipline. It involves using academic sources as nodes and tracing citations among them as lines to create a network graph. Figure 5 illustrates the citation network, where the size of each node is proportional to the total number of citations received, and the thickness of the connecting lines indicates the citation frequency between the nodes. The largest nodes belonged to the authors Brik A. (2009), Aliju Gros C. (2006), and Sarayu K. (2012), whose publications were most often cited and who played leading roles within this network. The names of the listed journals (e.g., *Desalination, J Environ Manage*, *Bioresource Technology*) indicate that these authors are leaders in water treatment, environmental science, and biotechnology.

Subject categories and journals

Publications on textile wastewater reuse spanned 60 Web of Science subject categories. Among these categories, the highest-ranked were Environmental Sciences with 442 publications (21.77%), Chemical Engineering with 373 publications (18.37%), Environmental Engineering with 314 publications (15.47%), Water Resources with 285 publications (14.04%), and Green and Sustainable Science and Technology with 96 publications (4.73%). Table 1 presents the top 20 Web of Science journal categories, along with their publication counts, percentage contributions, citations, and H-index values. The Web of Science database was used to retrieve citation metrics and the H-index for each category. The most publications

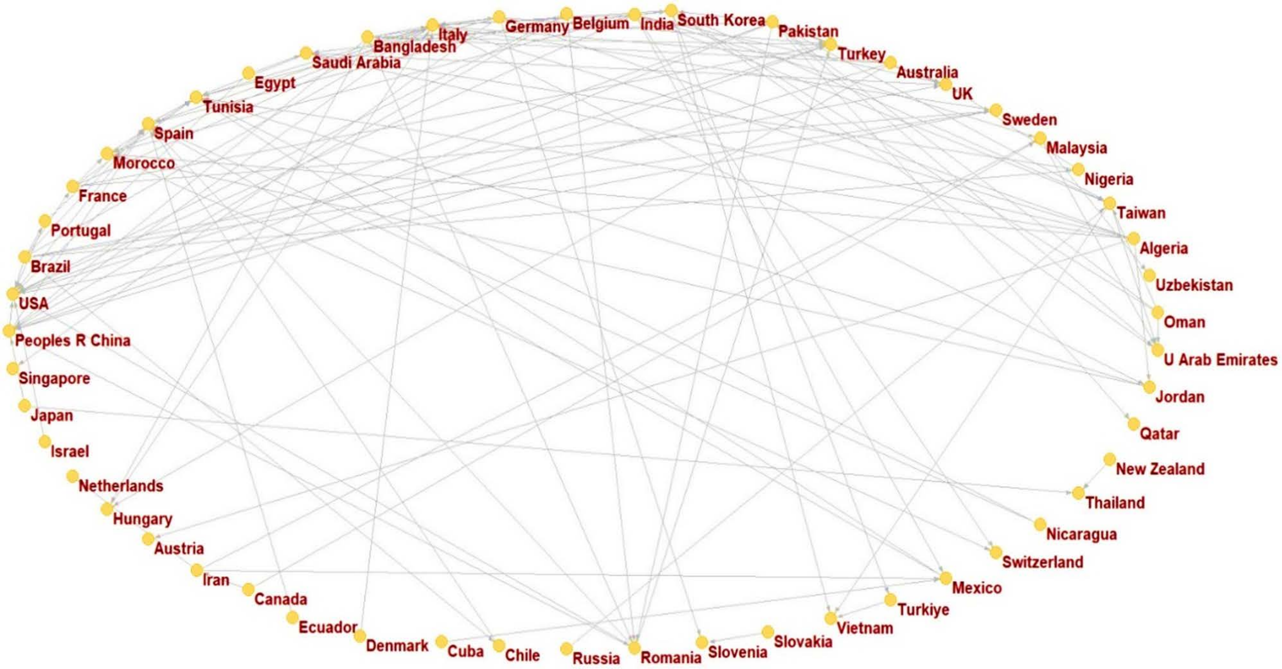

Figure 4. Country contributions

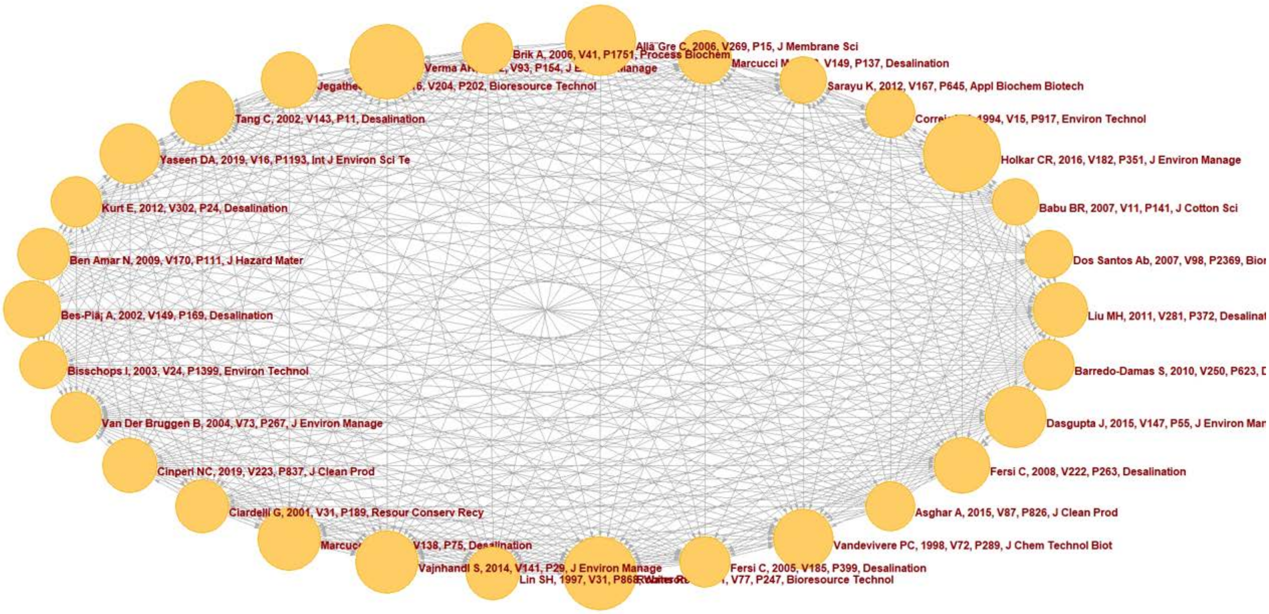

Figure 5. Citation network

were published in Environmental Sciences, but the most-cited article was in Chemistry: Physical, with an average citation of 39.97. Citation values were sourced from Web of Science; variations reflect differences in citation practices and research visibility across disciplines.

Research emphasis

Keyword analysis

A keyword network can be constructed from scientific publications, researchers, scientific journals, countries, research organizations, and other entities. VOSviewer was used to analyze keywords and identify the central research variables in the study of textile wastewater reuse. A total of 1232 keywords were extracted from the dataset. To explore various co-occurrence relationships some keywords were excluded by setting the minimum occurrence threshold to 8. Thus, 68 keywords meeting this requirement remained for the co-occurrence network map. Figure 6 visualizes the keyword overlay and density. In recent years, wastewater use has gained significant attention in research, particularly for its applications in irrigation and nutrient recovery.

Word cluster analysis

The word clusters revealed publication counts for topics such as wastewater treatment, water conservation, textile

Table 1. Top 20 Web of Science categories.

Sr. No.	WoS categories	Publications	Percentage contribution	Citation	H-index
1	Environmental Sciences	442	21.77%	33.18	59
2	Engineering Chemical	373	18.37%	36.34	67
3	Engineering Environmental	314	15.47%	39.63	60
4	Water Resources	285	14.04%	30.64	53
5	Green Sustainable Science Technology	96	4.73%	34.72	34
6	Chemistry Multidisciplinary	88	4.33%	20.92	19
7	Chemistry Physical	64	3.15%	39.97	25
8	Polymer Science	61	3.00%	28.13	22
9	Materials Science Multidisciplinary	57	2.81%	17.74	19
10	Materials Science Textiles	52	2.56%	12.98	13
11	Biotechnology Applied Microbiology	32	1.58%	29.31	16
12	Biochemistry Molecular Biology	26	1.28%	17.15	11
13	Chemistry Applied	24	1.18%	24.00	12
14	Physics Applied	24	1.18%	28.96	14
15	Energy Fuels	20	0.99%	22.95	10
16	Physics Condensed Matter	17	0.84%	29.00	10
17	Chemistry Analytical	16	0.79%	26.44	10
18	Nanoscience Nanotechnology	14	0.69%	35.36	10
19	Metallurgy Metallurgical Engineering	13	0.64%	20.92	9
20	Limnology	12	0.59%	7.42	6

industry, textiles, reuse, etc. Word clustering is a process of grouping texts that are similar in their content. It is easy to understand because it groups related documents. Word clustering can be used for information retrieval, text summarization, topic modeling, etc. There are various algorithms for word clustering, including K-means, hierarchical clustering, and neural network-based clustering. The word cluster results showed a continuously increasing publication output. Analysis shows not only that research activity is increasing, but also that awareness of wastewater reuse is growing.

Top cited publications

To determine the top 20 cited publications in the context of "Textile Wastewater Reuse," data were extracted from Web of Science by searching for the selected keywords. A total of 1324 articles were published from 2004–2025. Of the 37,473 articles, 36,668 were without self-citations. All the articles were cited 51,868 times, which equals 48,502 excluding self-citations. The average citations per article was 38.77, and the average H-index was 103. Table S1 represents the top 20 cited publications with source title, publication year, DOI of the article, total citations, and average annual citations of the article since publication. The most cited article was 'Tailored titanium dioxide photocatalysts for the degradation of organic dyes in wastewater treatment: A review,' published in 2009 in *Applied Catalysis A: General* by Han et al. Figure 7 represents the number of publications and the number of citations in each article on textile wastewater reuse. In 2022, highest number of published articles and citations were 134 and 5532, respectively; in 2023, the number of publications was only 113, but the citations reached a maximum of 5884. Over the entire publication span from 2005 to 2025, the highest number of articles was published and cited in the year 2024. The data were collected until August 2025, so the number of publications and citations in this year appear lower than in 2024.

PageRank analysis

Table S2 represents the findings of the PageRank study. In the table, Yaseen DA ranked first, indicating that their paper received the most citations from highly cited articles, rendering it a prestigious article in the field of textile wastewater reuse. A graph was drawn using Gephi software to analyze PageRank. Figure 8 presents the co-occurrence and the relationship among the highly cited articles. In the figure, larger nodes represent higher PageRank, and smaller nodes represent lower PageRank for the article. The curved lines represent relationships among articles.

Article on wastewater reuse

Industrial

The most important problems of the 21st century are water scarcity and environmental issues, driven by uneven distribution of resources, inadequate treatment, and climate change. Reused wastewater is considered another source of fresh water suitable for consumption. When selecting appropriate wastewater treatment and reuse strategies, one should consider local conditions, the plant's technological characteristics and economics, and the expected application of the wastewater. Treated wastewater from chemical industries is used for non-

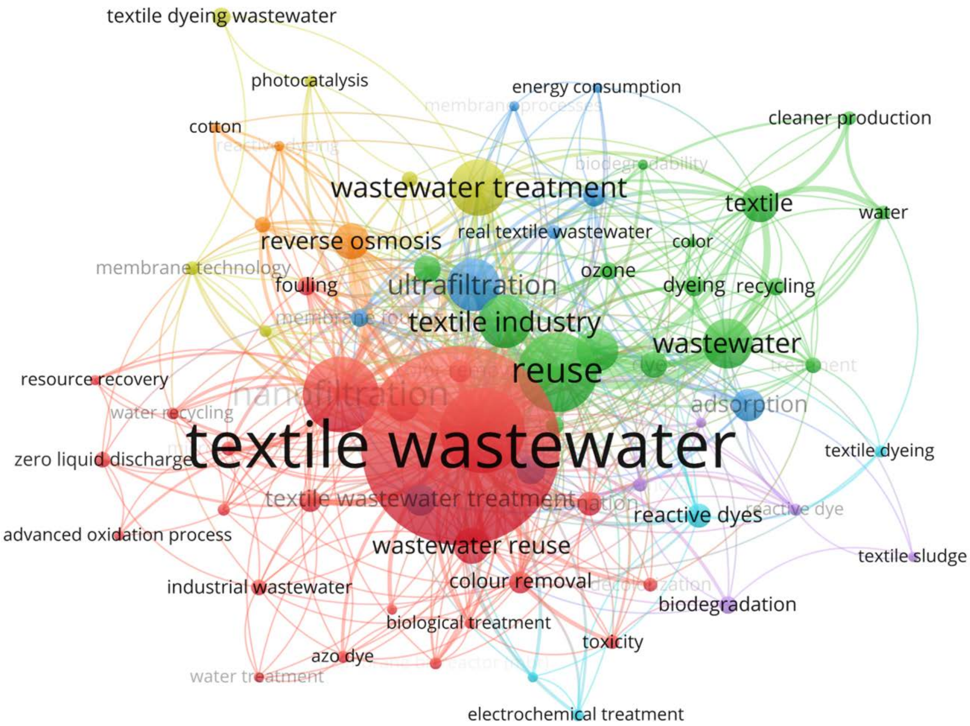

Figure 6. Keyword co-occurrence

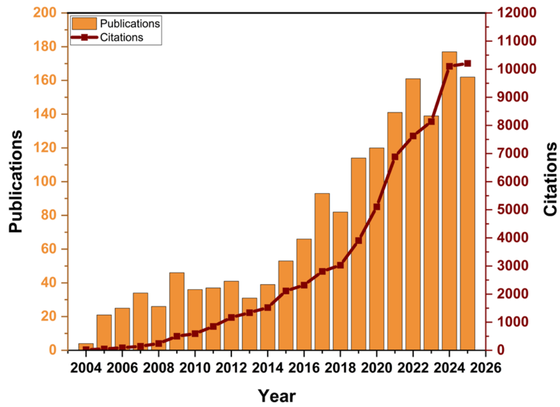

Figure 7. Annual publications (bars) and total citations (line) of textile wastewater reuse research

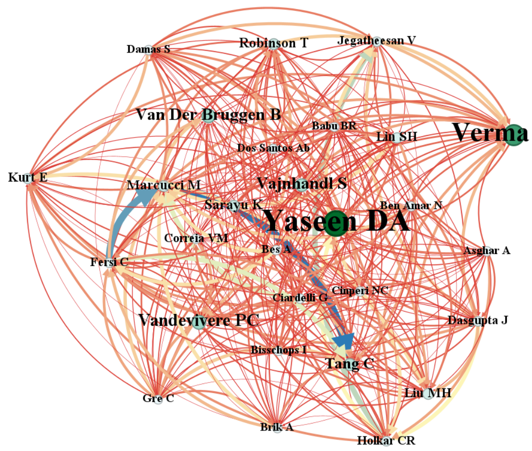

Figure 8. PageRank network

potable purposes. Wastewater reuse strategies aim to address the significant challenge of water scarcity without exacerbating other environmental problems. The S-Curve, shown in Figure 9(a), reveals the number of research articles in the field of textile wastewater reuse in industry over the years, with an R^2 value of 0.954. The data for the S-Curve were extracted from Web of Science using the keyword "Textile wastewater reuse in Industries." The maturity of the curve indicates that research in this domain is approaching saturation. Nevertheless, as illustrated in Figure 9, several categories have not yet attained this stage, indicating substantial opportunities for further investigation in these areas.

Irrigation

Agricultural water demand can be calculated using two methods: one based on a specified water depth and the other on evapotranspiration. The S-Curve shown in Figure 9(b) was created using Loglet Lab 4 to predict the volume of wastewater to be reused for irrigation, with a growth rate of 0.943 and an R^2 value of 0.943. The S-Curve data were extracted from Web of Science using the keyword "Textile wastewater reuse in Irrigation." The early stage of development represents a critical period for advancing research and focusing efforts in this area.

Construction

The development of transportation, water supply, and wastewater infrastructures has become a fundamental component of modern society. In tunnel construction, it removes suspended solids, turbidity, and soluble silica by chemical reaction and microfiltration. To predict the

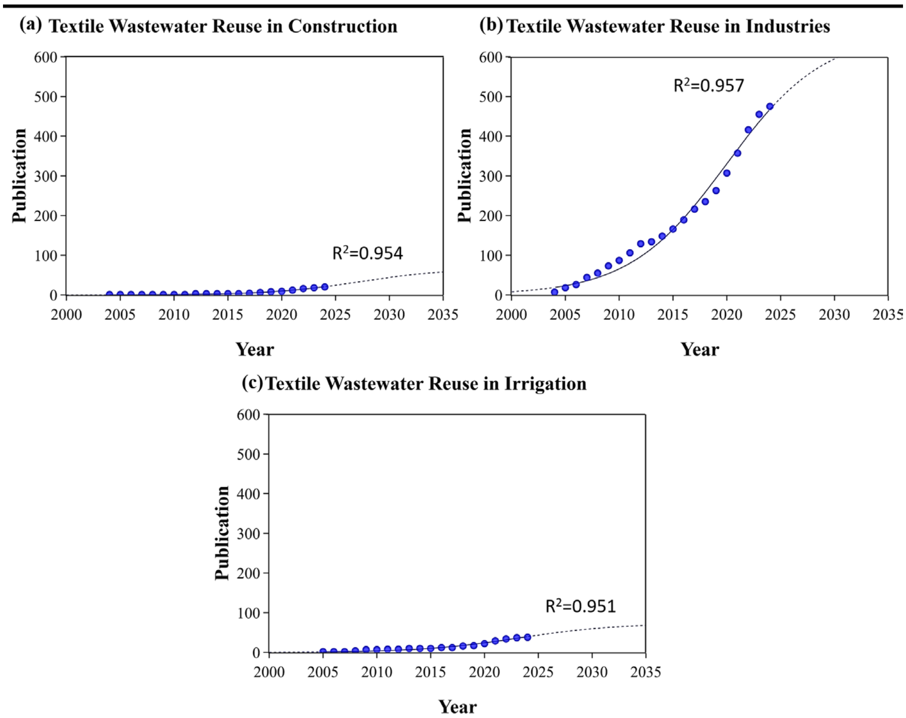

Figure 9. Consolidated S-Curves (a) Construction (b) Industry (c) Irrigation application

future development of wastewater reuse in construction areas, the S-Curve was used to project trends up to 2035, as shown in Figure 9(c). The model had an R^2 of 0.887. The S-Curve data were extracted from Web of Science using the keyword "Textile wastewater reuse in construction." Studies on the reuse of textile wastewater in construction are still at an early stage and present a significant opportunity for further research.

Patents

An analysis of patents pertaining to textile wastewater reuse was extracted from the Scopus database from 2004 to 2024. An S-Curve was also drawn to predict the future of industries, construction, and irrigation. The S-Curve shown in Figure 10 represents the trends in the number of patents issued over time in the wastewater reuse area, with R^2 values of 0.954 in construction, 0.957 in industries, and 0.951 in irrigation. The data for drawing the S-Curve for textile wastewater reuse was extracted from the Scopus database by searching the keywords (a) "Textile wastewater reuse in construction," (b) "Textile wastewater reuse in Industries," and (c) "Textile wastewater reuse in Irrigation." The reuse of wastewater in industries has reached a mature stage, but in construction and irrigation, it remains at an early stage of development. In construction and irrigation, fresh water is required because wastewater contains contaminants that make it unsuitable for these purposes, so wastewater is first treated to become suitable for these applications. In construction, high material strength is a primary requirement, and in agriculture, crops with lower sensitivity to contaminants are preferred. Therefore, freshwater or treated wastewater is required for these applications. This indicates that wastewater reuse is a key research focus in construction and irrigation applications.

Discussion

Israel reuses the highest amount of wastewater globally (about 84%) for irrigation (20). Spain currently reuses 5%, which is expected to increase to 20% in the future (21). Australia reuses 9% wastewater, which is projected to increase to 30% of their wastewater (22). These countries (Israel, Spain, and Australia), have published publications regarding the reuse of wastewater. Two examples of such publications are the *Australian Guidelines for Water Recycling Guidelines for Environmental Management: Use of Reclaimed Water*, and *Spanish Regulation for Water Reuse* (23- 25). In these countries, high environmental standards and guidelines for wastewater reuse are in place. The citation network is also used to investigate collaboration among these authors (26,27).

Articles related to textile wastewater utilization have received a notably high number of citations, approximately fivefold higher than the mean impact factor of the journals in which they were published. Publications focusing on textile wastewater utilization have received a considerable number of citations, reflecting the growing scientific relevance (28). Keyword analysis showed the direction of future research (29,30). Bibliometric keyword analysis was conducted by searching "Textile Wastewater Reuse" as a keyword. This analysis discovers research hotspots and scientific research trends. The keyword analysis and keyword mapping network were developed using VOSviewer version 1.6.20 (31-33).

PageRank, introduced by Brin and Page (1998), assigns a score to a page or article based on how many times highly

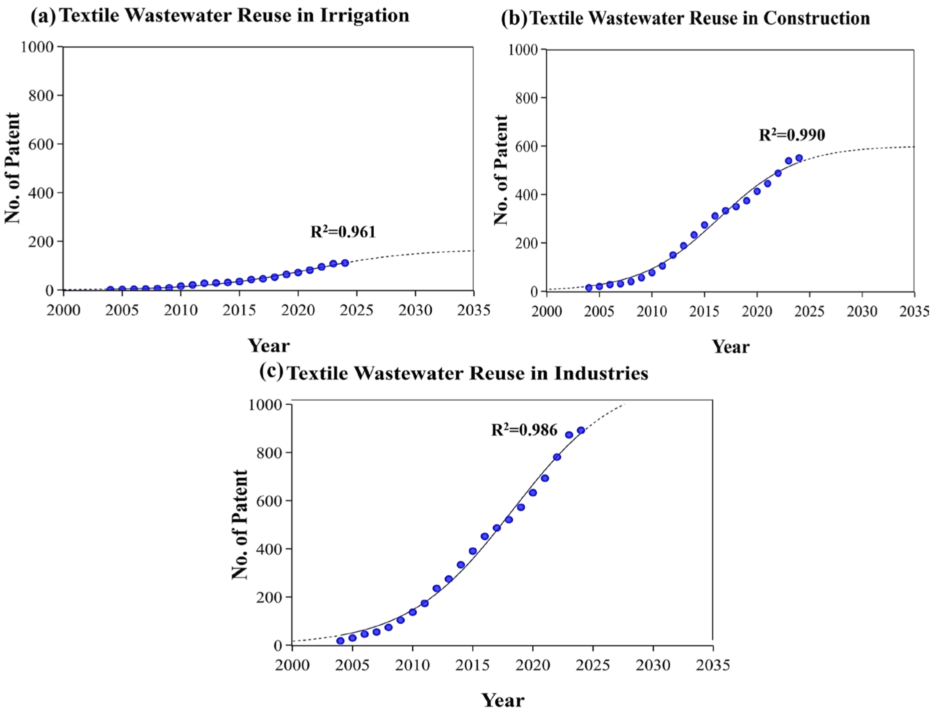

Figure 10. Consolidated patent trends in (a) Irrigation, (b) Construction, and (c) Industries

cited articles cite it. The PageRank analysis technique was used to assess an article's prestige. Initially, PageRank prioritized webpages, but later it was used to map articles published in various ways. PageRank was calculated using Gephi. The standard PageRank formula (Eq. 1) was used (34,35).

$$PR(A)=\frac{(1-d)}{N}+d\left(\frac{PT(k_1)}{C(k_1)}+\ldots+\frac{PT(k_n)}{C(k_n)}\right) \quad (1)$$

where, A is article cited by other articles $k_1, k_2, k_3, \ldots k_n$; $C(k_1)$ is the citation of paper k_1; PR(k_1) is PageRank and d is the damping factor. Brin and Page originally proposed a damping factor of 0.85 in the PageRank algorithm. N is the size of the network (36,37).

Textile wastewater is primarily used in cooling towers (38). After that, it is sent to secondary treatment; in wastewater treatment plants, wastewater is treated by coagulation-flocculation, micro-screen filtration, and two-stage sand filtration. Reverse osmosis purifies wastewater through membrane separation, and ultraviolet treatment is applied as a subsequent step to remove residual organic contaminants and microorganisms that may remain after membrane filtration. Finally, sodium hypochlorite is added for disinfection (39). The cost of textile wastewater treatment and reuse increases exponentially with increasing waste content removal efficiency (40, 41).

Freshwater availability is increasingly constrained by variable climatic conditions, such as fluctuating precipitation and snowpack levels (42). Concurrently, evolving land-use patterns and persistent agricultural demands have exacerbated groundwater depletion (43). To mitigate the resulting severe water deficits, the strategic reclamation and reuse of wastewater has become an essential global initiative. In the agricultural sector, advanced modeling frameworks are increasingly utilized to optimize both the treatment processes and the subsequent distribution of reclaimed wastewater for irrigation (44).

Beyond agriculture, the rapidly expanding global construction industry represents a massive sink for freshwater, primarily for concrete production. To alleviate the strain on potable water resources, researchers are investigating the use of treated industrial wastewater in concrete mixing. The viability of this approach depends heavily on the degree of water refinement. While the use of secondary-treated wastewater has been shown to reduce the compressive strength of concrete by 9% to 18%, the application of highly refined, reclaimed wastewater can actually enhance compressive strength by 8% to 17%. However, the successful integration of industrial effluents into secondary applications requires rigorous, specialized pretreatment. Textile wastewater, for instance, presents significant processing challenges before it can be converted into usable water. While chemical pretreatments such as calcium chloride (CaCl2) are employed, they often exacerbate steady-state flux decline, with membrane fouling accounting for over 80% of total filtration resistance (45, 46).

Consequently, such treated effluents must be carefully diluted prior to utilization in concrete mixing. To overcome these persistent treatment bottlenecks, current research is heavily focused on implementing advanced oxidation technologies. Implementing these diverse wastewater reclamation strategies at scale presents complex systemic challenges. This includes mitigating emerging contaminants, achieving carbon neutrality (carbon peak and synergy), and driving technological standardization and intelligent equipment innovation (47-49). It should be noted that Web of Science and Scopus are suitable databases for research on water reuse; the analysis in this manuscript is only based on these sources. Therefore, future work can be done on publications from other databases such as Google Scholar and PubMed. Currently, interest in environmental sustainability is rising; this is evident in pioneering developing countries such as India, China, Brazil, and South Africa. Therefore, it may be estimated that future research on textile wastewater reuse will take place in other developing countries facing water scarcity. Cooperation between universities and various institutions can advance knowledge on water reuse and play a significant role in promoting the sustainable use of water resources. Research on textile wastewater could focus more on energy saving and automated treatment systems to enable future reuse of water. To reuse wastewater, contaminants must be removed. Chong et al. investigated whether advanced oxidation processes (AOPs) have high removal efficiency in removing organic compounds from industrial wastewater (50). Therefore, advanced oxidation processes will have great value as pretreatment in the foreseeable future. Mao et al. studied the technological maturity of physical, chemical, and biological treatment in the industrial wastewater field and efficient wastewater reuse in various applications (51). Biological treatment is in the mature phase, but physical and chemical treatment are rapidly growing. Therefore, physical treatment warrants consideration for future research. The physical pretreatment method can separate and remove soluble, suspended, and non-soluble pollutants.

Conclusion

This paper conducted a thorough bibliometric study of global research on the reuse of textile wastewater from 2004 to 2025. The analysis revealed that scholarly interest has increased every year; the year 2024 had the highest number of publications, with more than 160 articles published. Among the total analyzed publications, 1324 (98.95%) were published in English, indicating that English-language publications hold the leading position in this field of research.

From the point of view of contribution, China was ahead with 274 (24.62%) articles, followed by India (118, 10.61%) and Turkey (104, 9.3%). The most articles appeared in journals specializing in environmental sciences (442; 20.31%), chemical engineering (373; 17.14%), and environmental engineering (314; 14.43%), which signify that research is highly multidisciplinary. Citation analysis showed 51,868 total citations, of which 48,502 were not self-citations; the annual citations per article were 38.77, and the total H-index of the data was 103. The article by Yaseen DA was the most influential in the PageRank analysis, as it was cited by the most highly cited articles.

Using keyword analysis in VOSviewer yielded 1232 keywords, 68 of which met a minimum frequency threshold of 8. This finding was used to define major research clusters and emerging themes. The S-curve patent analysis showed a mature stage (>20 years) for wastewater reuse in industrial applications and a very early stage for application in irrigation and construction. Though more than 500 articles are available on textile wastewater reuse, there has been little focus on its use in the construction industry and agriculture.

This data-driven paper systematically reviews the intellectual territory and research output in the domain of textile wastewater reuse. Its contribution lies in combining numerous bibliometric tools and visual analytics to report global trends and knowledge gaps. In future research, emphasis should be placed on applications that have not had very high representation worldwide, including reuse in irrigation and construction. Furthermore, research should focus on collaborative work across disciplines, the development of universal and affordable treatment technologies, and the integration of sustainability so that it can be practically applied across various industrial settings.

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Authors' Contribution

Conceptualization: Punyasloka Pattnaik
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Investigation: Pinkesh Kumar Sharma
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Resources: Vikas Kukshal
Supervision: Vikas Kukshal
Validation: Amar Patnaik
Visualization: Amar Patnaik
Writing–original draft: Pinkesh Kumar Sharma
Writing–review & editing: Pinkesh Kumar Sharma

Competing Interests

The authors declare that there are no competing interests.

Ethical Approval

The authors hereby certify that all data collected during the study are as stated in the manuscript, and no data from the study have been or will be published separately elsewhere.

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Supplementary Files

Supplementary File 1 contains Tables S1 and S2.

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