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Global Trends and Evolution of Ecotechnology in Textile Wastewater Treatment: 21-Year Bibliometric Analysis

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Abstract: The textile industry supports the global economy, but it produces dye-rich wastewater that poses a threat to ecosystems and human health. Conventional treatment methods are expensive, energy-demanding, and often unsustainable. This study examines global research trends in the application of ecotechnology for textile wastewater treatment from 2004 to 2024. Data were collected from Scopus on August 9, 2025, and analyzed using the PRISMA, Excel, and VOSviewer tools. A total of 413 peer-reviewed English papers were reviewed based on the keywords "ecotechnology" and "textile wastewater treatment." Research output has grown significantly since 2016, driven primarily by India and China. Core topics include constructed wetlands, adsorption, and phytoremediation, while recent studies highlight advanced materials, photocatalysis, nutrient recovery, and water conservation. These developments show a shift toward hybrid systems and circular economy models. Most papers appear in multidisciplinary journals, reflecting the broad and interconnected nature of the field. Yet, significant gaps remain in linking technology with social, policy, and behavioral aspects. Stronger collaboration across disciplines is needed to connect innovation, governance, and local engagement. Such efforts will help make ecotechnology a more sustainable and scalable solution for managing textile wastewater.

Keywords: Adsorption, bibliometric analysis, wetlands, nature-based solutions, textile effluent treatment, sustainability

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1. Introduction

The textile industry is a significant part of the global economy, supporting growth and providing millions of employment opportunities (Castillo-Suárez *et al.*, 2023; H. Khan & Kaur, 2024). Yet, it is also one of the largest sources of water pollution, producing substantial amounts of complex wastewater that harm both the environment and human health. Textile effluents contain toxic and persistent substances such as dyes, heavy metals, surfactants, and organic matter that are

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difficult to break down (Deng *et al.*, 2020; Gomaa *et al.*, 2023). When released into rivers and lakes without proper treatment, these pollutants damage aquatic life and ecosystems. Dyes block sunlight and slow photosynthesis, while heavy metals build up in sediments and organisms (Ajibade *et al.*, 2023). High levels of nutrients and organic matter lead to oxygen depletion, eutrophication, and loss of biodiversity. Together, these effects disturb the natural balance of ecosystems and weaken the services they provide (Khattab *et al.*, 2020; Zulti *et al.*, 2024). Understanding how technologies for treating textile wastewater have evolved is therefore essential for addressing environmental and social challenges in industrial areas. Because the impacts are severe and widespread, studying research trends in textile wastewater treatment has become increasingly important.

Conventional treatments such as coagulation–flocculation, activated sludge, and chemical oxidation are widely used for textile wastewater (Neto *et al.*, 2024; Odhaib & Jaeel, 2023). However, these methods often need high energy, create large amounts of sludge, and are less effective at removing new contaminants (Al Prol, 2019). These limits show the need for treatment options that are more sustainable, adaptable, and environmentally friendly.

Ecotechnology has emerged as a promising nature-based approach that applies ecosystem principles to solve environmental problems (Camano *et al.*, 2014). By using natural processes and materials, it offers a cost-effective and resilient way to clean wastewater (Aba *et al.*, 2024). In textile wastewater treatment, ecotechnology includes constructed wetlands, adsorption with natural materials, and phytoremediation using aquatic plants. These systems lower pollutant levels, restore ecosystem functions, improve resilience, and support circular economy goals (Vo *et al.*, 2023).

Research on textile wastewater ecotechnology shows strong pollutant removal performance, often reaching over 80% for ammonia and 60% for dyes. These results are achieved through systems such as constructed wetlands and natural adsorbents like bentonite. Combining several ecotechnologies, such as wetlands with adsorption or phytoremediation, has become a promising approach to enhance treatment efficiency (Susanti *et al.*, 2023). However, there are still a few studies that provide a comprehensive overview of the connections between global research trends, collaboration networks, and sustainability outcomes. Most existing reviews focus on technology performance and case studies, without using bibliometric or network approaches to map broader patterns of innovation and cooperation.

Over the past twenty-one years, research on ecotechnology for textile wastewater treatment has experienced rapid growth, driven by global efforts toward sustainability and the development of nature-based solutions. The 21 years from 2004 to 2024 were chosen to illustrate how this field has evolved during key milestones in sustainability, including the Millennium Development Goals (2000–2015) and the Sustainable Development Goals (2015–2030). This timeline offers a clear view of how international collaboration, innovation, and policy focus have impacted the progress and application of ecotechnology in the textile industry.

Even with this progress, many studies still examine ecotechnology in isolation, looking at single case studies or methods without connecting results across different regions (Yusuf et al., 2020). Only a few explore how research networks, innovation sharing, or global collaboration have evolved. Most reviews stay centered on technology, focusing on how well specific methods work and their limitations. They predominantly address the effectiveness, limitations, and operational aspects of particular treatment methods—such as advanced oxidation processes, membrane filtration, biological treatments, and hybrid systems (Ceretta et al., 2021; Jahan et al., 2022; Kallawar & Bhanvase, 2023). To address this gap, we present a systematic bibliometric review covering a 21-year, leading to the following research questions:

1. How has ecotechnology research in textile wastewater treatment developed over the past two decades?
2. Which countries, institutions, and authors have had the greatest influence on this field?

3. Which journals and document types have most supported the spread of this research?
4. What gaps and opportunities remain for future innovation?

This study aims to analyze global publication trends related to the use of ecotechnology in textile wastewater treatment over the past twenty-one years. It identifies the most influential countries, institutions, authors, journals, and main document types. The analysis visualizes research productivity, impact, and thematic links through keyword co-occurrence and overlay analysis. It also highlights research gaps and offers insights for future studies from both global and Indonesia-specific perspectives.

2. Theoretical background

2.1. Ecotechnology

Ecotechnology merges ecological science and engineering to develop solutions for environmental issues and encourages harmony between human activities and natural processes while reducing environmental harm (Jorgensen, 2020; Kangas, 2019). As a nature-based approach, ecotechnology highlights sustainability, resilience, and long-term ecological stability (Costanza, 2012; Mitsch & Mander, 2017; Stoffers *et al.*, 2021). It has evolved into a cross-disciplinary approach applied in various fields, including water treatment, agriculture, and natural resource management (Silva, 2023).

Constructed wetlands, ecological agricultural practices, and natural filtration systems are practical applications of ecotechnologies. These approaches utilize plants, microorganisms, and natural materials to perform essential ecosystem functions, such as removing pollutants and maintaining environmental quality (Ji *et al.*, 2022; Nuamah *et al.*, 2020). The goals are to reduce energy consumption, reduce dependence on chemicals, and restore ecosystem services that support environmental sustainability (Arenas-Castro *et al.*, 2018).

A nature-based approach is a sustainable solution that offers environmental, social, and economic benefits while addressing practical challenges (Li & Hai, 2023; Scarpellini *et al.*, 2020). It utilizes local resources, promotes community involvement, and combines knowledge (Bauermann *et al.*, 2024). These features make it an essential tool for sustainable development and circular economy practices; however, it remains limited by the need for large land areas, seasonal variations that affect performance, and obstacles such as maintenance issues and long startup times. These factors underscore the importance of adaptive management and integrated planning for the effective deployment of ecotechnology (Flores-Nieves *et al.*, 2022; Gustafsson *et al.*, 2019).

2.2. Textile Wastewater

Textile wastewater produces large amounts of pollutants from dyeing, washing, and finishing processes. Common pollutants include synthetic dyes and Chemical oxygen demand (COD). COD levels are reported from 200 to over 4,000 mg/L, depending on the production process, which exceeds discharge standards (<200 mg/L) (Ariza-Pineda et al., 2023). Dye molecules, with their complex aromatic structures, are highly resistant to natural biodegradation and can persist for long periods in sediments and water bodies (Lin et al., 2023; Vacchi et al., 2017). Additionally, some dyes release toxic or mutagenic byproducts, which increases ecological stress and poses potential long-term risks to human health and ecosystems (Dutta et al., 2024; Lellis et al., 2019; Ramamurthy et al., 2024). The complex composition of wastewater renders single treatment methods ineffective, often necessitating a combination of physical, chemical, and biological approaches.

Conventional methods such as coagulation, activated sludge, and advanced oxidation have been used to reduce pollutants, especially color and COD. However, these methods are not effective since they require a significant amount of energy. Large amounts of sludge also create new challenges for further treatment. Persistent compounds, especially complex synthetic dyes, remain challenging to break down even with these techniques (Ahsan et al., 2023; Nidheesh et al., 2022). These limitations emphasize the need for alternative, more efficient, sustainable, and environmentally friendly solutions.

2.3. Application of Ecotechnology in Textile Wastewater Treatment

Constructed wetlands (CWs) have shown promising results in treating textile effluent by combining plant-based phytoremediation and microbial processes within engineered substrates. Various studies report that CWs achieved 60–85% COD reduction, 65–90% BOD removal, and up to 70–90% dye removal, depending on plant species, system design, and hydraulic retention time (Etana et al., 2025; Hussain *et al.*, 2018). CWs also significantly remove ammonia by up to 70–80%, phosphorus by up to 40–65%, and suspended solids by as much as 80–95% (Henny *et al.*, 2022). Commonly used plants, such as Canna indica, Typha latifolia, and Phragmites australis, play a dual role by directly absorbing nutrients and dyes (Angmo *et al.*, 2024; Klink, 2017; Kumari & Tripathi, 2015), while their root systems provide oxygen and surface area that enhance the microbial degradation of organic compounds (Sheoran & Singh, 2024; Soana *et al.*, 2025).

Different configurations result in different outcomes. Subsurface flow wetlands effectively remove dyes and COD (Herrera-Melián et al., 2020; Sartori et al., 2016). Surface flow wetlands are more effective at reducing suspended solids and nutrients (Ennabili & Radoux, 2022). When combined, these systems form hybrids that provide a more comprehensive treatment, often removing over 80% of pollutants across multiple parameters (Sharma & Malaviya, 2022). Floating wetlands made from Eichhornia crassipes have also shown promising results in removing color and nutrients from ponds and natural water bodies (Sahreen & Mukhtar, 2023). CWs remain a sustainable option for textile wastewater because they are low-cost, produce little sludge, and are easy to maintain. However, challenges still exist, including large land requirements, system optimization, and reduced performance for persistent dye compounds.

Algal systems are gaining wide attention for treating textile wastewater. Both microalgae and macroalgae can remove nitrogen and phosphorus while breaking down synthetic dyes such as Crystal Violet and Reactive Blue through biosorption and biodegradation (Selvaraj *et al.*, 2022). Algal ponds and photobioreactors have demonstrated high nutrient removal rates, achieving up to 96% for nitrogen and 98% for phosphorus, through suspended-solid phase systems and immobilized algae (Özgür & Göncü, 2023; Tang et al., 2018; Yan et al., 2023). This dual ability makes algae suitable for combining wastewater treatment with the production of valuable biomass, which can later be used for biofuels or fertilizers, supporting a circular economy in wastewater management (Khan et al., 2022).

Integrated ecological systems combine plants, microbes, and algae to achieve better performance. These systems utilize multiple biological pathways simultaneously to enhance the removal of pollutants. Hybrid wetlands that combine wetland plants with algae have shown strong results in removing dyes and nutrients. Such integrated ecotechnologies are practical, sustainable, and increasingly used in pilot and full-scale textile wastewater treatment projects (Dell'Osbel *et al.*, 2020).

3. Materials and Methods

Previous studies show that bibliometric analysis usually includes three main steps: defining the research question, doing the analysis, and presenting the results (Donthu *et al.*, 2021). In this study, the research question is introduced in the Introduction section, while the analytical steps, based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, are illustrated in Figure 1. The findings are presented and discussed in the Results and Discussion section. The PRISMA framework provides a clear and structured process for identifying, screening, and selecting studies. This method ensured that only relevant and reliable publications were included in the analysis.

3.1. Setting Search Items

A bibliographic search was conducted in the Scopus database for peer-reviewed literature across scientific disciplines. Scopus was chosen because it offers reliable indexing, broad journal coverage, and accurate citation tracking for global research (Baas *et al.*, 2020). The search focused on publications related to "ecotechnology" and "textile wastewater treatment." Main keywords were combined with synonyms such as "textile industry", "textile wastewater", "ecotechnology", "environmentally friendly technology", and "constructed wetlands". Data were collected on 9 August 2025 for studies published between 2004 and 2024.

3.2. Inclusion Criteria and Article Selection

The inclusion criteria covered peer-reviewed English papers that examined ecotechnology in wastewater or textile effluent treatment. Exclusion criteria were applied to eliminate studies that did not address ecotechnology or nature-based treatment methods. Articles were excluded if they did not discuss approaches such as constructed wetlands, phytoremediation, biosorbents, biochar, microbial-based treatment, aquatic macrophytes, or similar ecological technologies applied to textile wastewater. A language filter limited the dataset to English publications from 2004 to 2024. During screening, 19 non-English papers were removed from the original 432 records. The final dataset comprised 413 articles, which were used for detailed analysis.

3.3 Conducting Initial Data and Bibliometrics Analysis

The dataset was organized in Microsoft Excel to support descriptive statistical analysis. This analysis shows publication trends, citation counts, major journals, leading institutions, contributing countries, and document types. The results provide an overview of research growth, productivity, and global distribution. Bibliometric mapping and network analysis were carried out using VOSviewer version 1.6.19. The analysis included keyword co-occurrence, overlay visualization, and co-authorship mapping. The mapping highlights research themes, emerging topics, and collaboration networks among authors. Overlay and density maps reveal a shift from traditional approaches to modern, sustainable technologies. Together, these results give a clear picture of the research landscape and connections in textile wastewater studies.

4. Results and Discussion

4.1. Research Trends by Year

Publication trends over the last 21 years show a clear rise in studies on ecotechnology for treating textile wastewater (Figure 2). Between 2004 and 2016, research activity was limited, marking an early stage with little academic attention (Halepoto *et al.*, 2022; Islam *et al.*, 2024). After 2017, the number of studies began to grow steadily and increased sharply after 2019. This growth reflects the expanding interest in sustainable, nature-based approaches such as constructed wetlands and integrated systems (Behera *et al.*, 2021; Hussain *et al.*, 2018, 2019). Research from the past five years highlights the increasing importance of ecotechnology in addressing environmental issues associated with textile production (Rahman *et al.*, 2020). The steady increase in studies shows that this topic has become a key area for researchers, practitioners, and policymakers to explore and apply (Bahara *et al.*, 2025).

Figure 3 shows the different patterns between research growth and academic influence. From 2004 to 2010, citations peaked in 2005 (3,287) and 2007 (3,291), while publication numbers were still low. These early studies had a profound impact and laid the foundation for subsequent research (Holkar *et al.*, 2016). Between 2011 and 2018, citation counts declined and fluctuated at lower levels, despite the number of publications continuing to rise. Each new paper added to the field but had less individual influence. Since 2019, research output has increased significantly, reaching over 60 papers per year in 2022–2023. This steady rise indicates a growing global interest in ecotechnologies for treating textile wastewater. Citation numbers remain moderate, suggesting that the field is now more diverse, with broader participation rather than being driven by only a few landmark studies.

The analysis shows that research on ecotechnology for textile wastewater treatment has entered a mature phase. Publications have proliferated, and citations now appear across a broader range of studies. Research is becoming more diverse, moving beyond dependence on a few early works. Similar observations were made by Sharma and Malaviya (2022), who noted topic expansion and stronger international collaboration as signs of progress in the field.

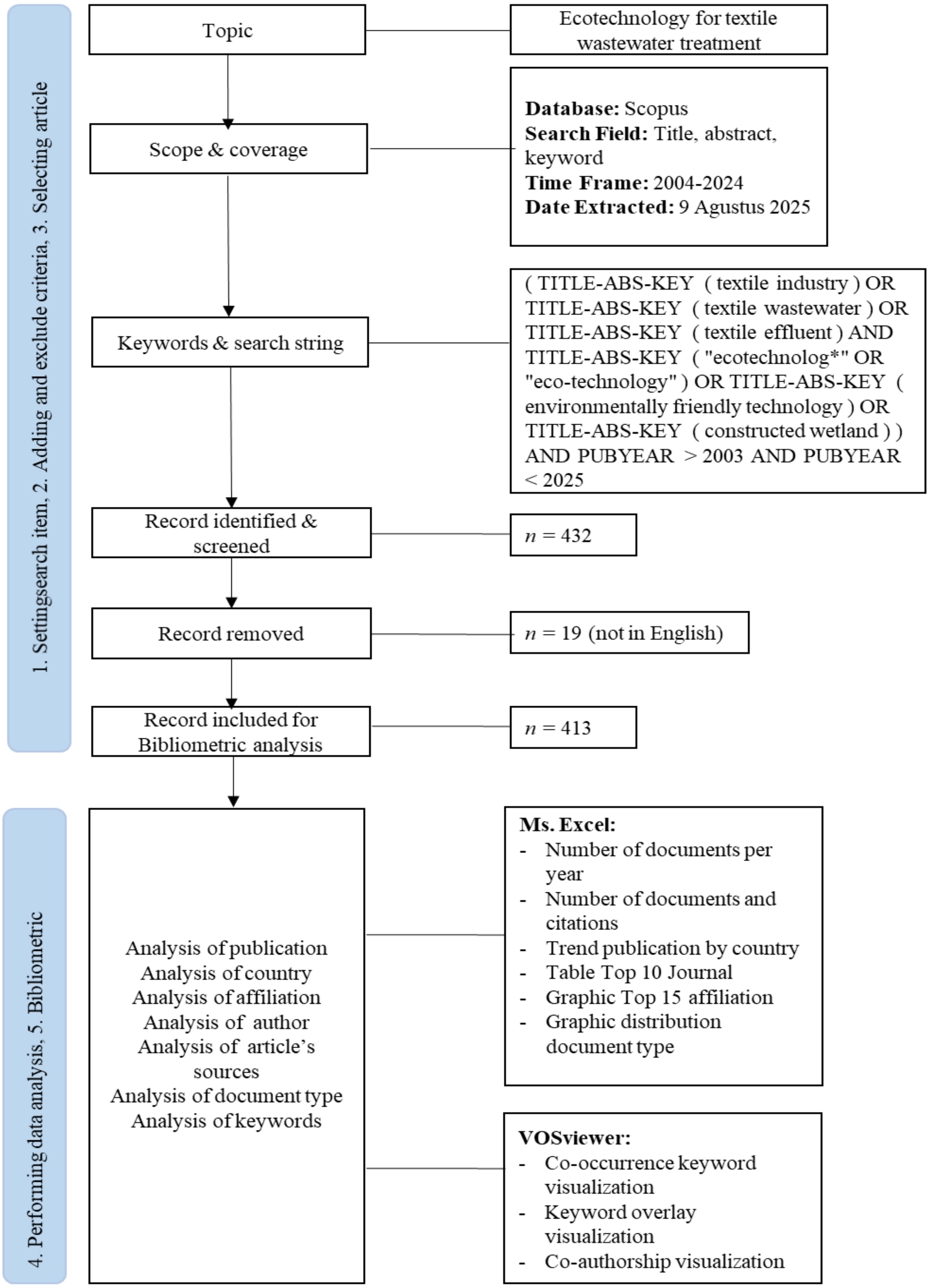

Figure 1. Flowchart of the process of selecting papers for bibliometric analysis

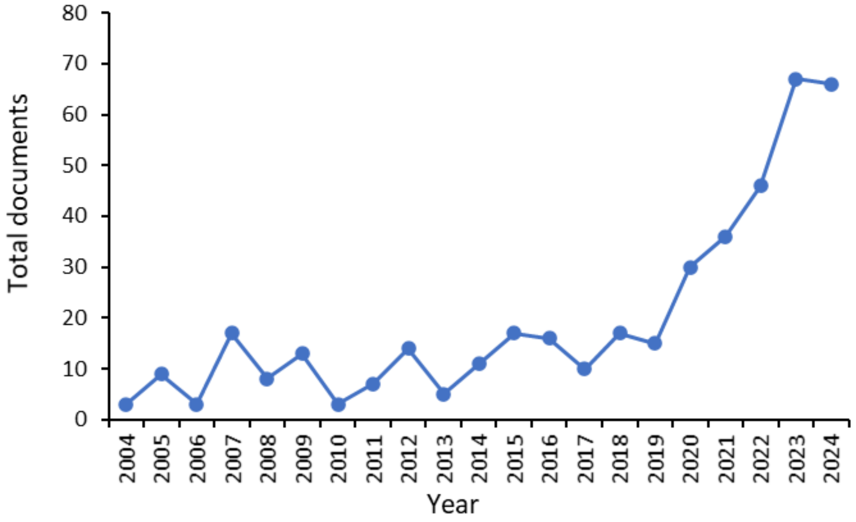

Figure 2. Development of ecotechnology publications for textile wastewater treatment 2004-2024

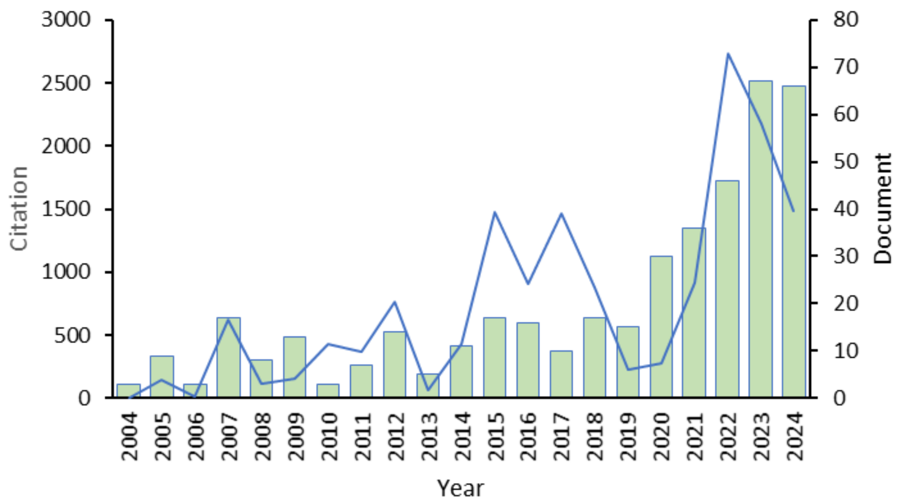

Figure 3. Number of documents and citations on textile wastewater treatment ecotechnology in the last 21 years

4.2. Geographical Distribution of Research

The global distribution of studies on ecotechnology for textile wastewater treatment shows apparent regional differences (Figure 4). Asia leads the field, reflecting its role as the center of textile production. North America and Europe contribute at moderate levels, while South America, Africa, and Oceania show limited research activity. This pattern suggests that research is concentrated in regions facing high industrial activity and intense environmental pressures.

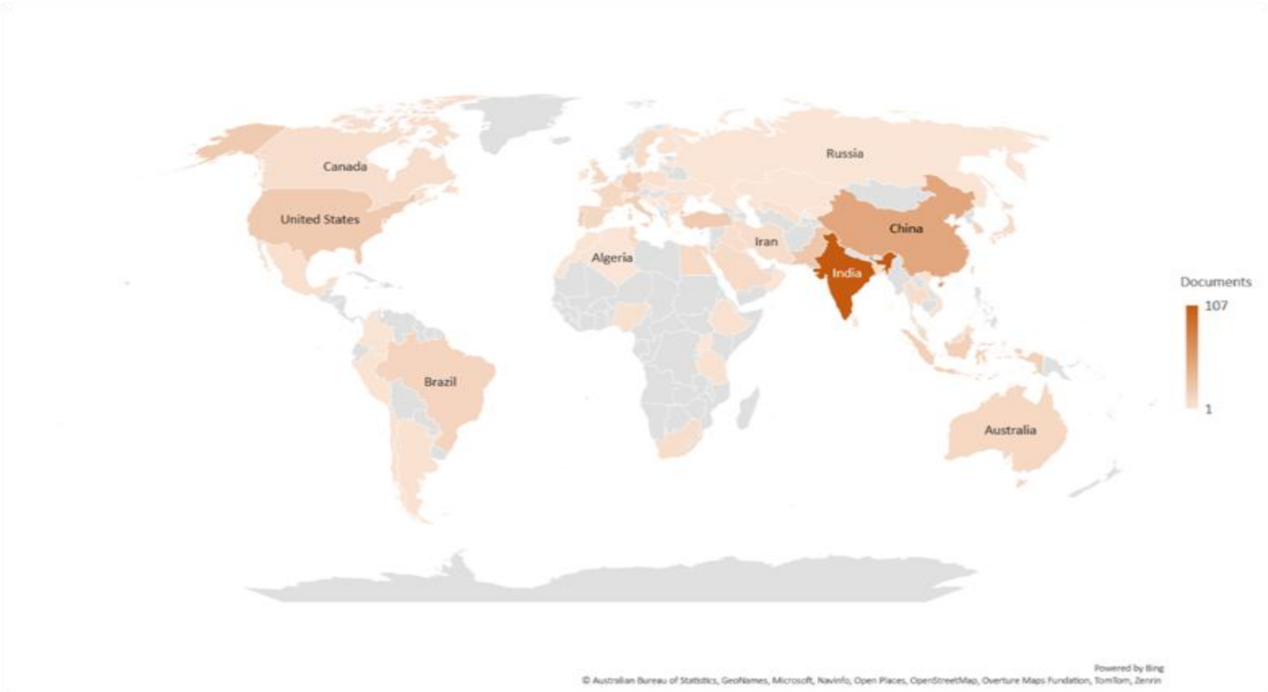

Figure 4. Global distribution of publications on ecotechnology for textile wastewater treatment over the past 21 years

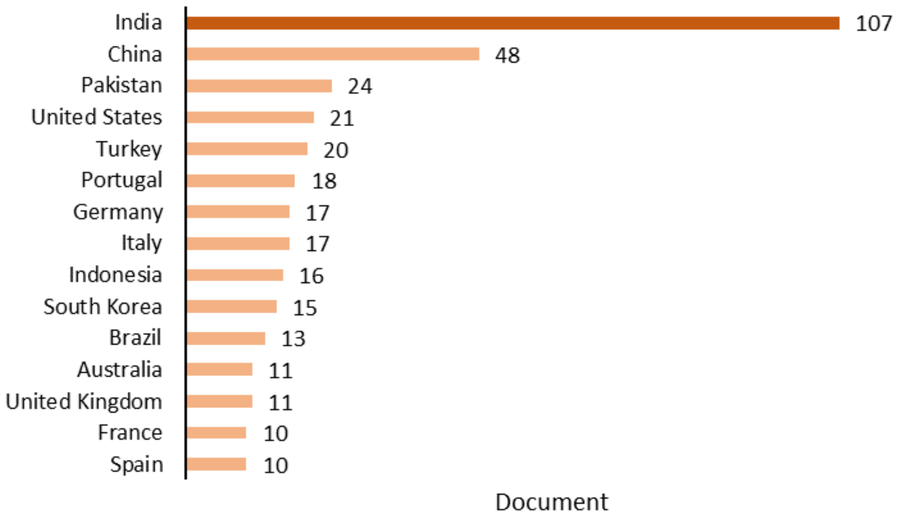

Figure 5. Number of documents on ecotechnology for textile wastewater treatment from up to 15 countries worldwide.

At the country level (Figure 5), India leads with 107 publications, reflecting its large textile industry and ongoing challenges in waste management (Pattnaik *et al.*, 2018). China follows with 48 papers, confirming its major role in textile production and growing commitment to sustainable processing (Lyu *et al.*, 2021). Pakistan (24) and the United States (21) also contribute significantly, illustrating that both developing nations face industry challenges and developed countries possess strong research capacities and robust environmental regulations. Turkey (20) and several European countries, such as Portugal (18), Germany (17), and Italy (17), demonstrate active participation, supported by both academic and industrial interest in sustainable textile technologies.

In Asia, alongside India and China, Indonesia (16) and South Korea (15) also made significant research contributions. This shows that awareness of textile wastewater issues is growing in countries with expanding industries. From other regions, Brazil (13) represents South America, while Australia (11) reflects the continent's active role in Oceania. The United Kingdom (11), France (10), and Spain (10) complete the top 15, demonstrating Europe's collective effort to promote sustainable textile wastewater management globally.

Asia's leading role in this field shows that the growth of ecotechnology research relies not only on advanced technology but also on how accessible, affordable, simple, and practical it is for real-world use (Sohaimi *et al.*, 2023). India emphasizes practical applications using local materials, while China combines simple methods with innovations suited for large-scale industries (Gyamfi et al., 2024; Geng *et al.*, 2021). The rapid progress of research in Asia reflects a close link between local environmental needs and global sustainability goals.

4.3. Analysis Based on Article Sources

Publications on ecotechnology in textile wastewater treatment are published in numerous journals and conference proceedings. This indicates that both academic journals and conferences play a crucial role in disseminating knowledge in this field. The IOP Conference Series: Earth and Environmental Science was the leading platform, highlighting the value of conferences in presenting new ideas. Among peer-reviewed journals, Water Science and Technology (9 papers) and Environmental Science and Pollution Research (8 papers) were the most active in publishing studies on applied environmental engineering and pollution control.

Table 1 shows that high-impact journals, such as Science of the Total Environment and Chemosphere, demonstrate how ecotechnology research bridges different scientific fields. Technical journals, such as the Journal of Water Process Engineering and Desalination and Water Treatment, focus on the engineering aspects of sustainable treatment technologies. The Journal of Cleaner Production links this work to sustainability and circular economy goals, while the Journal of Hazardous Materials highlights concerns about toxicity and risk control. Ecological Engineering emphasizes the value of nature-based systems, such as constructed wetlands, in improving wastewater treatment. Together, these journals demonstrate that ecotechnology research is shifting from a primarily technical approach to one that also incorporates environmental sustainability. This expands earlier studies that focused more on technology than on ecological integration (Behera *et al.*, 2021; S. A. R. Khan *et al.*, 2022).

Table 1. Top 10 leading publication sources on ecotechnology for textile wastewater treatment

No	Journal Name	Number of documents
1	IOP Earth and Environmental Sciences Conference Series	11
2	Water Science and Technology	9
3	Environmental Science and Pollution Research	8
4	Science of the Total Environment	8
5	Chemosphere	7
6	Journal of Water Process Engineering	7
7	Desalination and Water Treatment	6
8	Journal of Cleaner Production	6
9	Hazardous Materials Journal	6
10	Ecological Engineering	5

4.4. Analysis by Affiliation

Author affiliations reveal the distribution of research on ecotechnology across global institutions. Figure 6 illustrates the primary organizations most frequently associated with publications in this field. The National Natural Science Foundation of China (NSFC) leads with 17 publications, followed by the Higher Education Commission of Pakistan (HEC) and the University Grants Commission (UGC) with nine each. The Ministry of Science and Technology, India (MoST), contributed eight papers, while Portugal's Fundação para a Ciência e a Tecnologia (FCT) supported seven, and India's Science and Engineering Research Board (SERB) produced six. Other contributors include CAPES (Brazil) and China's National Key

Research and Development Program (NKRDP), each with five papers. The China Scholarship Council (CSC) and TÜBİTAK (Turkey) followed with four, while CNPq (Brazil), the European Regional Development Fund (ERDF), FAPESP (Brazil), the Japan Society for the Promotion of Science (JSPS), and King Saud University (KSU, Saudi Arabia) each produced three.

This pattern indicates that support for ecotechnology research extends not only to developed nations but also to emerging economies with substantial textile industries. Countries such as China, India, Pakistan, Brazil, and Turkey play active roles in developing innovative and sustainable solutions. Their growing participation reflects the global importance of ecotechnology and its shared goal of improving wastewater management worldwide (Urbina-Suarez *et al.*, 2024).

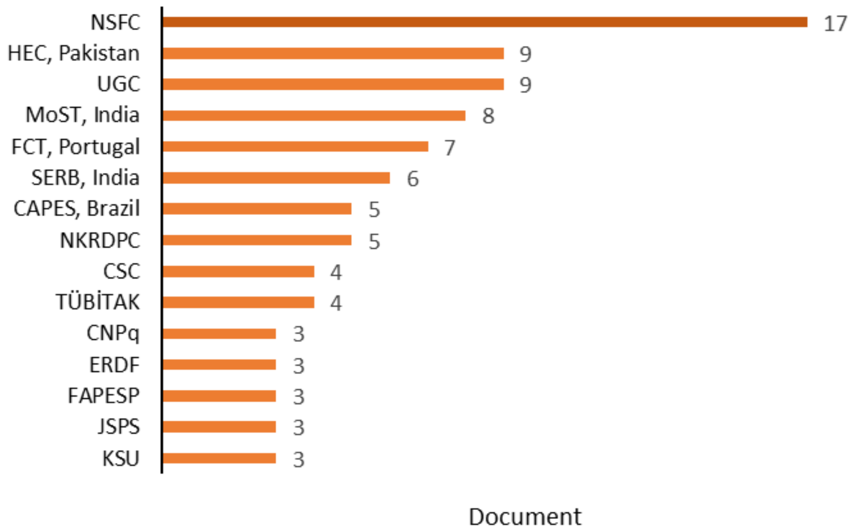

Figure 6. Top 15 affiliates researching ecotechnology for textile wastewater treatment.

4.5. Analysis by Document Type

The distribution of document types (Figure 7a) shows that most publications are research articles (55%), followed by reviews (18%), book chapters (15%), and conference papers (9%). A smaller portion includes books (2%) and conference reviews (1%). The large share of articles shows a focus on publishing original research, while the many reviews indicate a growing effort to summarize existing studies (Ruiz-Sánchez *et al.*, 2024). The share of book chapters suggests a wider dissemination of ecotechnology work in academic volumes, and the conference papers demonstrate the value of academic meetings for sharing early results and fostering collaboration.

The subject area distribution (Figure 7b) shows that Environmental Science leads (23%), followed by Engineering (16%), Materials Science (12%), and Chemical Engineering (9%). Other active areas include Chemistry (7%), Business and Management (6%), Energy (5%), Biochemistry and Molecular Biology (5%), and Agricultural and Biological Sciences (5%). In contrast, Earth and Planetary Sciences (3%), Immunology and Microbiology (2%), Medicine (2%), Physics and Astronomy (2%), Computer Science (2%), and Social Sciences (1%) contribute less. The strong presence of environmental and engineering fields reflects a focus on practical, technology-driven solutions such as new adsorbents, catalysts, and treatment systems. The more minor role of social sciences points to a gap in understanding the socioeconomic, policy, and behavioral factors that influence the adoption of ecotechnologies—a pattern also seen in broader environmental research (Abdullah & Azizan, 2024).

Ecotechnology research is still primarily led by technical work, with substantial input from natural science and engineering fields. Progress in the future will depend on teamwork across disciplines that connects new technology with policy and social understanding. This approach is crucial for achieving tangible improvements and sustainable results in textile wastewater management.

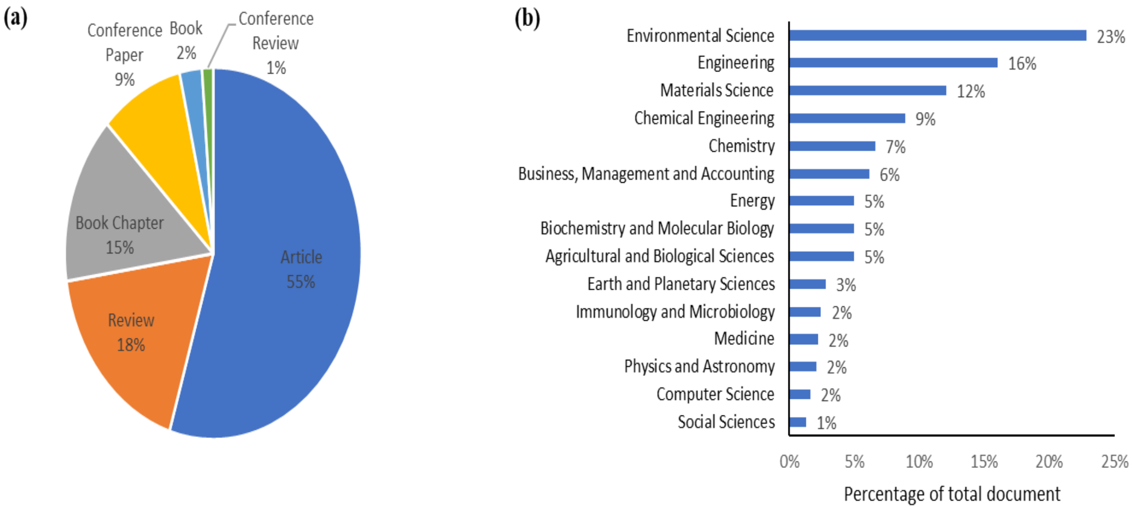

Figure 7. Distribution of publications on ecotechnology for textile wastewater treatment by (a) document type and (b) subject area.

4.6. Analysis by Author

The co-authorship network highlights the collaborative structure of research on ecotechnology for textile wastewater treatment over the past 21 years, considering only authors with at least three publications (Figure 8). Each node represents an author (with size reflecting publication volume), links indicate co-authorship ties, and colors represent collaboration clusters, which often align with thematic or regional research groups (Ariel Xu & Chang, 2020). The green cluster is the largest, with Afzal M. and Arslan M. leading strong partnerships with colleagues such as Iqbal S. and Rehman K., who study phytoremediation and constructed wetlands. The red cluster, centered on Han W. and Wang X., represents a major Chinese group focused on microalgae and nutrient recovery. The blue cluster, led by Rodrigues L.R. and Oliveira G.A., highlights wetland and natural treatment research in Europe and South America. Smaller groups include the yellow cluster (Asghar H.N. and Mohsin M.) and the purple cluster (Ali S. and Rizwan M.), which explore microbial and plant-based treatment systems.

Afzal and Han are key leaders in collaboration networks, each leading strong research hubs in South Asia and China. Their work shows that regional partnerships drive much of the progress in ecotechnology for textile wastewater treatment, while smaller teams add focused expertise that expands the field’s diversity (Scherbakova & Bredikhin, 2021).

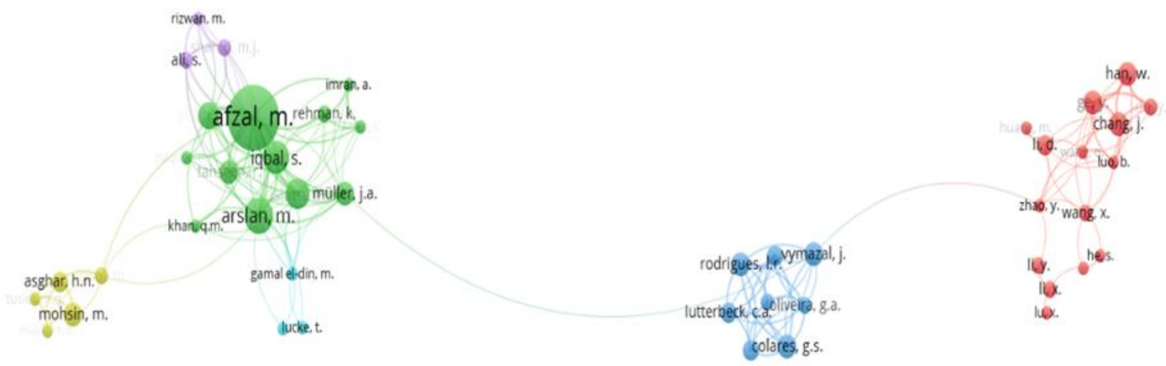

Figure 8. Co-authorship network of researchers working on ecotechnology for textile wastewater treatment over the past 21 years

4.7. Analysis Based on Keywords

The keyword co-occurrence map in Figure 9 shows a visual overview dividing research into four main clusters. The blue cluster represents environmental engineering, marked by keywords such as wastewater treatment, constructed wetlands, COD, and waste. This cluster highlights the dominance of studies using constructed wetlands to remove COD, nitrogen, and heavy metals (Hussein, 2023; Saba *et al*., 2015). The red cluster focuses on the textile industry, featuring terms like dyes, adsorption, and photocatalysis. It reflects the rise of advanced materials and hybrid adsorption–photocatalytic techniques for degrading synthetic dyes in real wastewater (Munonde *et al*., 2025). The green cluster includes biological approaches such as bioremediation, phytoremediation, and enzymes, showing the role of microbes and plants in breaking down dyes and transforming pollutants (Parihar *et al*., 2022). The yellow cluster, though smaller, centers on pollutants like nitrogen and heavy metals, and includes terms such as biochar and water conservation. It points to targeted removal strategies tested in horizontal-flow wetlands and adsorption-based studies (Junio *et al*., 2024).

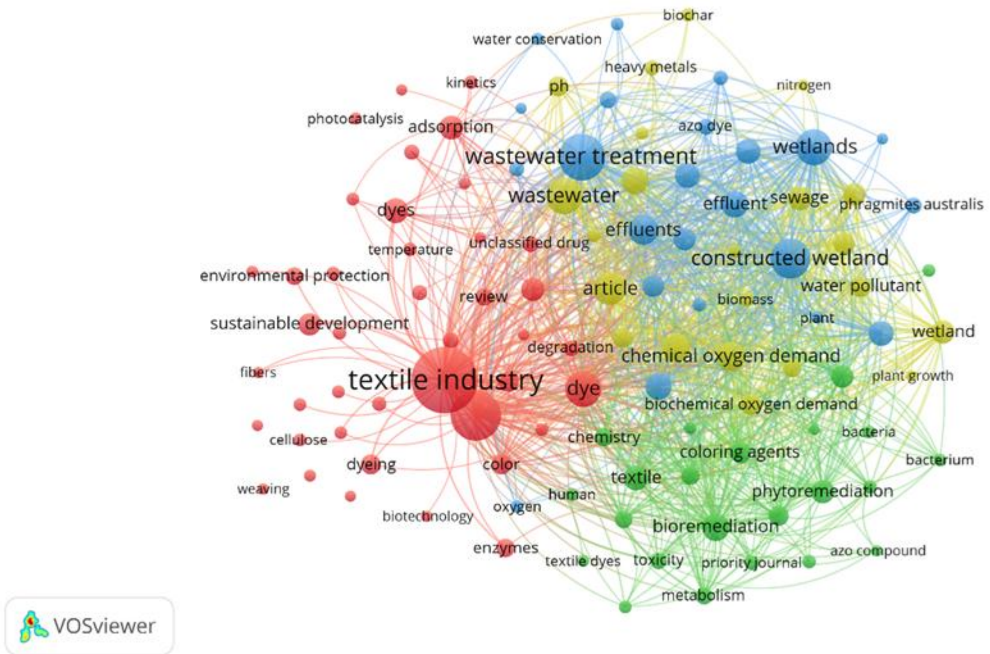

Figure 9. Visualization of frequently appearing keywords in ecotechnology for textile wastewater treatment over the past 21 years

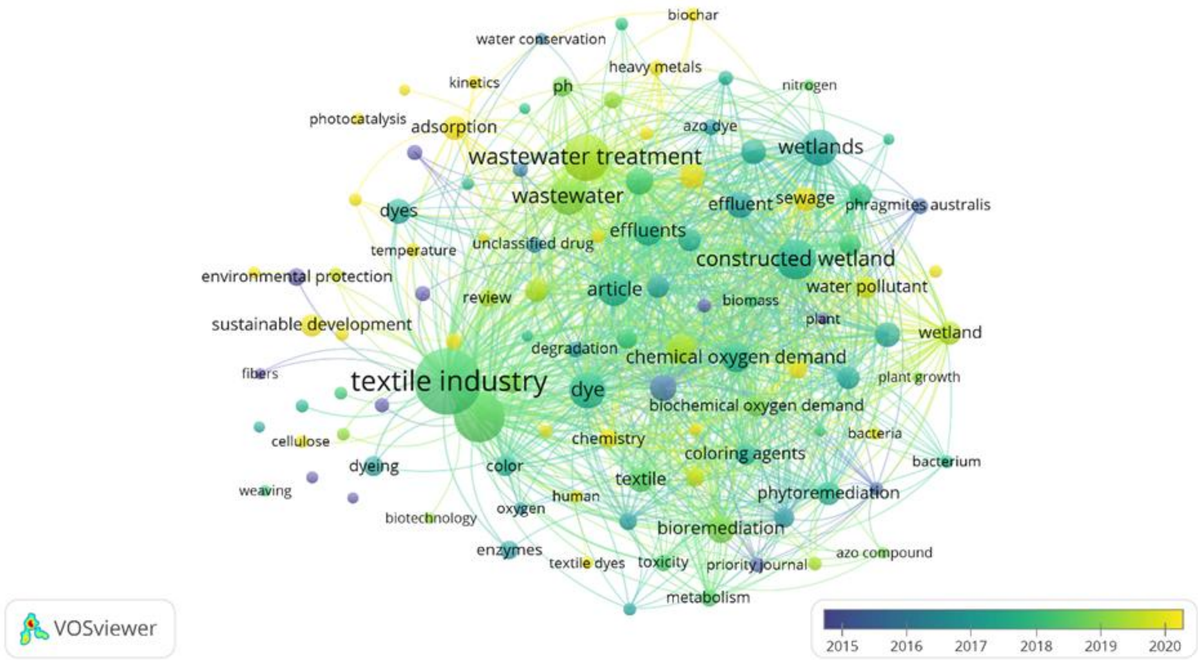

Figure 10. Visualization of overlays that frequently appear in ecotechnology for textile wastewater treatment over the past 21 years

The overlay map in Figure 10 illustrates the evolution of research themes in textile wastewater treatment over time. Early work from 2015 to 2017, shown in green and blue nodes, focused on the textile industry, wastewater treatment, constructed wetlands, and bioremediation. More recent studies from 2019 to 2020, shown in yellow, highlight growing interest in biochar, heavy metals, pH, adsorption, photocatalysis, water conservation, and nitrogen. This change marks a move toward material-based methods, targeted contaminant removal, and sustainable water management. Interest in biochar and photocatalysis reflects the search for affordable, high-performance adsorbents and light-driven treatment processes (Fazal *et al.*, 2020; Jebelli *et al.*, 2024). Growing attention to water conservation and nitrogen control also shows a focus on resource recovery and nutrient reuse (Wongkiew *et al.*, 2024). Overall, these trends show a shift from traditional methods to innovative, multifunctional, and eco-friendly technologies that support circular economy goals and sustainable development.

4.8. Implications and future research

This section discusses the main research gaps found in the bibliometric analysis and outlines future directions at both global and Indonesia-specific levels.

4.8.1. Global Perspective

The bibliometric review shows that research on ecotechnology for textile wastewater treatment has become more diverse and widespread, yet several gaps remain. Most studies still focus on technical and engineering aspects, with limited attention to policy, social, and community factors that are necessary for long-term sustainability. Although Asian countries have made significant progress by linking local environmental challenges to global sustainability goals, the absence of global comparative frameworks makes it challenging to integrate regional findings into shared strategies. Recent studies highlight growing interest in materials such as biochar and in processes like adsorption and photocatalysis. However, questions about their long-term performance, scalability, and environmental impact remain unanswered. These issues highlight the need for collaboration across disciplines and sectors to bridge the gap between technological progress and policy and social relevance.

Hybrid systems that combine adsorption, photocatalysis, and biological treatment show strong potential for industrial wastewater. Future research should also explore nutrient recovery, in situ remediation, pH stabilization, and ecological monitoring using bioindicators (Sethulekshmi & Chakraborty, 2021). Broader collaboration and investment in nature-based systems—such as constructed wetlands and floating treatment beds—are gaining global attention and deserve continued support.

4.8.2. Indonesia-Specific Context

Indonesia's tropical water systems face unique challenges due to seasonal monsoons, high pollution loads, and the presence of small-scale industries like batik production (Daud *et al.*, 2022; Widyarani *et al.*, 2022). These conditions require low-cost, adaptable treatment systems that combine science, field application, and supportive policy (Sutapa *et al.*, 2021). Hybrid systems designed for Indonesia's conditions, such as phytoremediation–adsorption methods using native plants like *Canna indica* and *Vetiveria zizanioides*, supported by local materials like bentonite and zeolite, have shown promising results. Studies report that Floating Treatment Wetlands (FTW), Constructed Wetlands (CW), and fixed-bed reactors can significantly reduce COD and dye concentrations (Zulti *et al.*, 2025). Using bioindicators like *Daphnia magna* helps assess both chemical and ecological outcomes.

Nature-based systems are suitable for small and medium-sized enterprises, especially in textile and batik production (Pratiwi *et al.*, 2018). Pilot projects in West Java demonstrate that CW and FTW units can effectively lower organic matter, dyes, and nutrients. Locally sourced bentonite and zeolite enhance the system's stability, particularly during the rainy season when pollutant loads increase.

Policy and funding programs should formally recognize nature-based solutions as key tools in national wastewater management. Existing Ministry of Environment (KLH) regulations on constructed wetlands could be expanded to encourage their wider use in the textile and batik sectors. Collaborative, cluster-based models, such as those in Pekalongan and Solo, which combine anaerobic pre-treatment, CW/FTW systems, and mineral-based polishing, offer practical examples for sustainable and affordable industrial wastewater management (Effendi *et al.*, 2018; Rahmadyanti & Wiyono, 2020).

5. Conclusion

This study shows that ecotechnology is becoming increasingly important for managing textile wastewater worldwide. Research has moved from traditional engineering toward new, sustainable methods that fit circular economy goals. The analysis gives a clear picture of research growth and global cooperation, especially across Asia. Still, social, policy, and economic issues are rarely explored. These gaps slow large-scale use and real-world application. Future studies should include life-cycle assessment, better policy support, and locally designed hybrid systems. Work in developing countries like Indonesia is needed to connect environmental innovation with community and economic benefits. Together, these efforts will make textile wastewater management more sustainable and practical.

Data availability statement

The data included and used in this study is not confidential and is available upon request.

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Conflict of interests

All authors declare that they have no conflicts of interest related to the writing or submission of this manuscript.

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Author Contributions

FZ, as the primary contributor, conceptualized the study and data analysis and wrote the original article. **DI, AMF**, and **DS** participated in the manuscript writing, review, editing, and supervision.

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