Chapter 6

Natural and Biosorbent Adsorbents for Decolorization of Azo Dyes: A Bibliometric Analysis of Global Research Trends

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Abstract

Natural and biosorbent adsorbents, sourced from agricultural and industrial by-products, have emerged as promising alternatives for the removal of azo dyes from wastewater. These materials, characterized by their abundance, cost-effectiveness, and environmental sustainability, offer significant advantages over conventional treatment methods. This bibliometric analysis investigates 489 publications from 1998 to 2025 indexed in the Web of Science, employing the Bibliometrix package in R for data extraction, analysis, and visualization. The prevailing research focus is on the synthesis, characterization, and performance evaluation of natural and biosorbent materials (e.g., agricultural waste, biomass, mineral clays) for the removal of conventional contaminants such as azo dyes. These materials have been studied for their adsorption mechanisms, including isotherms and kinetics, and their integration into hybrid treatment strategies combining physical, chemical, and biological processes. Moreover, recent studies highlight the exploration of modified adsorbents and nanocomposites to enhance adsorption capacity and efficiency. Despite considerable advancements, challenges remain regarding adsorbent regeneration, scalability, and techno-economic viability. This study provides a comprehensive synthesis of global research trends on natural and biosorbent adsorbents for azo dye removal, offering valuable insights into current progress, thematic evolution, and future directions in sustainable wastewater treatment technologies.

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1. Introduction

1.1. Background

Azo dyes, containing one or more azo (–N=N–) bonds, are widely used in industries such as textiles, leather, paper, and food. Their vivid color palette and cost-effectiveness make them particularly attractive (Benkhaya et al., 2020; Slama et al., 2021). However, the discharge of azo dye-laden effluents into aquatic systems poses significant environmental and public health risks, including genotoxicity, mutagenicity, and carcinogenicity (Malik et al., 2018; Keshava et al., 2023). The recalcitrant nature of these dyes, coupled with their resistance to conventional wastewater treatment processes, necessitates the development and deployment of advanced and sustainable remediation technologies (El-Sayed et al., 2024).

Among the diverse treatment methodologies explored for azo dye removal, adsorption using natural and biosorbent materials has gained prominence due to its simplicity, cost-effectiveness, and eco-friendly characteristics (Hardyanti et al., 2023; Mohan et al., 2014). Biosorbents derived from agricultural and industrial by-products, such as tea waste, rice husk, biochar, and various biomass materials, offer promising prospects for efficient dye removal while supporting the principles of circular economy and waste valorization (Irawan et al., 2020; Wang et al., 2018). Recent research has also highlighted the synergistic potential of integrating adsorption with biological and advanced oxidation processes, further enhancing the efficacy of azo dye remediation (Sarkar et al., 2017; Wang et al., 2021). Integrated treatment strategies, which synergistically combine physical, chemical, and biological processes, have been demonstrated to enhance the decolorization efficiency of azo dye-containing wastewaters (Argun et al., 2023).

1.2. The Significance of Azo Dye Pollution

Azo dyes, characterized by their vivid hues and durability, are extensively utilized in textile and leather industries across the globe (Mahmood et al., 2016; Goswami et al., 2024). However, the improper disposal and inadequate treatment of these synthetic dyes have precipitated severe environmental and health concerns. These issues are particularly acute in developing countries, where industrial wastewater management systems often lack the sophistication required to mitigate the release of such pollutants into natural ecosystems (Islam & Mostafa, 2019; Dutta et al., 2024).

The environmental ramifications of azo dye pollution are multifaceted. In aquatic ecosystems, these dyes contribute to significant water pollution,

reducing light penetration and disrupting photosynthesis, which in turn diminishes oxygen availability and threatens aquatic biodiversity (Goswami et al., 2024; Sornaly et al., 2024). Moreover, the persistence of azo dyes in water bodies exacerbates contamination, as many of these compounds are resistant to natural biodegradation processes (Mahmood et al., 2016). Soil contamination is also a critical issue, as improper disposal of dye-laden sludge can degrade soil quality, disrupt microbial activity, and facilitate the bioaccumulation of toxic compounds in the food chain (Hoque et al., 2024; Dutta et al., 2024).

The human health implications of azo dye pollution are equally alarming. Communities residing near industrial zones are exposed through various pathways, including contaminated water and crops, as well as direct skin contact (Goswami et al., 2024; Dutta et al., 2024). Azo dyes and their metabolic byproducts, such as aromatic amines, are recognized for their carcinogenic and mutagenic potential, capable of inducing genetic mutations and increasing cancer risk (Goswami et al., 2024; Dutta et al., 2024). Additionally, these compounds can trigger allergic reactions and skin irritation, particularly among workers in dye-intensive industries (Goswami et al., 2024; Dutta et al., 2024). Table 1 summarizes the primary environmental and health impacts of azo dye contamination, encapsulating key treatment strategies explored to address this global issue.

Table 1. Environmental and Health Impacts of Azo Dyes

Impact/Effect	**Description**	**Citation**
Water Pollution	Contamination of rivers, lakes, and groundwater, leading to long-term environmental damage	(Mahmood et al., 2016; Goswami et al., 2024)
Soil Pollution	Degradation of soil quality, affecting plant growth and microbial activities	(Hoque et al., 2024; Dutta et al., 2024)
Impact on Aquatic Life	Reduction of light penetration, inhibition of photosynthesis, and death of aquatic organisms	(Goswami et al., 2024; Sornaly et al., 2024)
Human Health Risks	Exposure through contaminated water, food, or direct contact, leading to various health issues	(Goswami et al., 2024; Dutta et al., 2024)
Carcinogenic and Mutagenic Effects	Increased risk of cancer and genetic mutations due to harmful intermediates	(Goswami et al., 2024; Dutta et al., 2024)
Allergenic and Irritant Effects	Skin inflammation, hypersensitivity, and other dermatological issues	(Goswami et al., 2024; Dutta et al., 2024)
Biological Treatment Methods	Use of microorganisms like bacteria, fungi, and algae for dye degradation	(Mahmood et al., 2016; Sornaly et al., 2024)

Enzymatic Degradation	Role of azoreductase, laccases, and peroxidases in dye breakdown	(Mahmood et al., 2016; Sornaly et al., 2024)
Advanced Bioremediation Strategies	Use of microbial consortia, genetically modified microorganisms, and nanotechnology	(Ali et al., 2023; Tripathi et al., 2023)
Physical and Chemical Treatment Methods	Methods like adsorption, ozonation, and electrochemical combustion	(Global Scenario and Technologies for the Treatment of Textile Wastewater, 2023; Patel et al., 2024)
Hybrid Treatment Systems	Integration of biological and physicochemical methods for higher removal efficiencies	(Patel et al., 2024; Tripathi et al., 2023)

Efforts to mitigate the adverse impacts of azo dye pollution have led to the development of diverse treatment strategies. Biological treatment methods leveraging bacteria, fungi, and algae have demonstrated promising results in degrading azo dyes into less harmful compounds (Mahmood et al., 2016; Sornaly et al., 2024). Enzymatic degradation, facilitated by enzymes such as azoreductases, laccases, and peroxidases, is a key mechanism underlying these biological processes (Mahmood et al., 2016; Sornaly et al., 2024). Advanced bioremediation approaches—including the use of microbial consortia, genetically modified organisms, and nanotechnology—have further enhanced degradation efficiency and treatment efficacy (Ali et al., 2023; Tripathi et al., 2023).

In contrast, traditional physical and chemical methods such as adsorption, ozonation, and electrochemical oxidation have been employed but often fall short due to high operational costs, generation of secondary pollutants, and incomplete dye mineralization (Global Scenario and Technologies for the Treatment of Textile Wastewater, 2023; Patel et al., 2024). Hybrid treatment systems integrating biological and physicochemical approaches represent a promising avenue to overcome these limitations and achieve comprehensive pollutant removal (Patel et al., 2024; Tripathi et al., 2023).

In summary, azo dye pollution constitutes a pressing global challenge with significant ecological and public health ramifications. Its disproportionate impact on developing regions underscores the urgent need for comprehensive regulatory frameworks, investment in sustainable treatment technologies, and the promotion of environmentally conscious industrial practices.

1.3. Objectives of the Study

In light of the environmental and health significance of azo dye pollution and the growing interest in sustainable remediation technologies,

bibliometric analyses provide a robust framework to systematically assess the evolution of scientific research in this field, identify leading contributors, track thematic trends, and highlight emerging frontiers. While several studies have conducted bibliometric evaluations on adsorption technologies and wastewater treatment in general (Hardyanti et al., 2023), a focused bibliometric review specifically targeting the use of natural and biosorbent adsorbents for azo dye decolorization remains limited. This gap necessitates a comprehensive assessment that elucidates research dynamics, international collaboration networks, and key thematic clusters in the context of azo dye remediation using sustainable adsorbents.

Therefore, the present study aims to conduct a detailed bibliometric analysis of global research trends on natural and biosorbent adsorbents for azo dye decolorization. Drawing upon 489 academic publications archived in the Web of Science (WoS) between 1998 and 2025, the analysis explores publication patterns, citation metrics, geographical distributions, international collaborations, and thematic keyword clusters. The selection of the WoS database ensures the inclusion of high-quality, multidisciplinary literature, supported by robust indexing and citation analysis tools (Rinanda et al., 2023). Data analysis and visualization were performed using the *bibliometrix* package in R (Aria & Cuccurullo, 2017). The findings of this study are expected to provide valuable insights into the scientific landscape of azo dye remediation, identify critical research gaps, and inform future directions for sustainable wastewater treatment technologies.

2. Material and Methods

2.1. Data Source and Search Strategy

This bibliometric analysis was conducted using the WoS Core Collection as the primary data source. The WoS was selected for its comprehensive coverage of multidisciplinary research areas, including natural sciences, social sciences, and engineering, as well as its robust citation analysis capabilities and data quality (Rinanda et al., 2023). Alternative databases such as Scopus and PubMed were considered, but WoS was ultimately chosen for its transparency, extensive citation metrics, and reliability in bibliometric research.

The literature search was performed on June 1, 2025, employing a targeted search strategy to retrieve publications relevant to azo dye decolorization using natural and biosorbent adsorbents. The search query was constructed using the following Topic Search (TS) keywords:

TS=(("azo dye*" OR "azo dyes" OR "textile dye*" OR "wastewater dye*") AND (decolorization OR "color removal" OR "colour removal" OR "dye removal") AND (biosorbent* OR "natural adsorbent*" OR "sustainable adsorbent*" OR "biological adsorbent*" OR "biobased adsorbent*" OR "low-cost adsorbent*") AND (adsorption OR bioremediation OR "wastewater treatment" OR "textile wastewater" OR "water treatment" OR "water pollution"))

The search was limited to publications in the English language and restricted to articles and reviews to ensure the inclusion of peer-reviewed and high-quality sources. As a result, a total of 489 publications were identified covering the period from 1998 to 2025.

2.2. Data Analysis and Visualization

The extracted bibliographic data were exported from WoS in plain text format and analyzed using the bibliometrix package (Aria & Cuccurullo, 2017) within the R statistical software environment. Bibliometrix offers a comprehensive suite of tools for conducting science mapping analyses, including performance analysis, collaboration analysis, and conceptual structure analysis. The analysis followed the technical workflow depicted in Figure 1.

Key bibliometric indicators assessed included:

- Publication trends over time (number of publications per year),
- Citation metrics (total citations, average citations per publication),
- Geographical distribution of publications (countries and regions contributing to the research),
- International collaboration networks (co-authorship analysis),
- Keyword co-occurrence networks to identify thematic clusters and research trends.

Visualization outputs such as network maps, histograms, and trend graphs were generated using bibliometrix and further refined for clarity. The analysis was designed to provide a comprehensive overview of global research dynamics and highlight key contributors, thematic foci, and gaps in the literature.

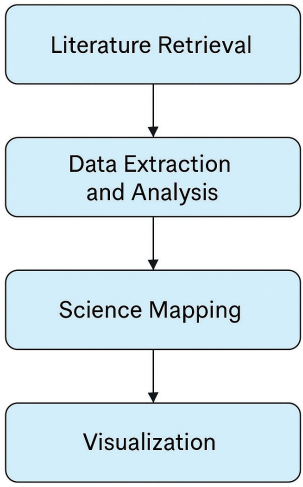

Figure 1. Bibliometric Analysis Workflow

3. Results and Discussion

3.1. General Characteristics of the Literature

The bibliometric analysis conducted in this study revealed a total of 489 publications indexed in the WoS between 1998 and 2025 focusing on natural and biosorbent adsorbents for azo dye decolorization. These publications are distributed across 191 distinct sources, including journals, book chapters, and conference proceedings. The analysis highlights an annual growth rate of 11.3%, reflecting a consistent and accelerating interest in sustainable dye removal technologies over the past decades. The average age of the documents was 8.55 years, indicating that both foundational and contemporary research efforts have significantly contributed to the field.

The document types include 458 research articles. The average citations per document was 78.74, underlining the relevance and impact of these studies within the scientific community.

A total of 1,747 authors contributed to this body of literature, with an average of 4.31 co-authors per document, demonstrating the collaborative nature of research in this area. The international co-authorship rate was 22.7%, highlighting the global interest and cooperation in developing sustainable solutions for azo dye remediation. The occurrence of 15 single-authored documents and 14 single authors suggests that while collaboration predominates, individual contributions also play a role in advancing the field.

The thematic breadth of the literature is evident from the 1,165 author keywords and 836 Keywords Plus, indicating a diverse range of topics and research directions. These bibliometric indicators are visually summarized in Figure 2, providing a clear and comprehensive overview of the dataset characteristics.

Figure 2. Summary of Key Bibliometric Indicators for the Analyzed Publications

These results reveal a robust and dynamic research landscape characterized by a growing scholarly interest, high-impact publications, and diverse international collaborations. The substantial number of citations per document reflects the recognition of this field's significance in addressing the pressing issue of azo dye contamination in wastewater. Furthermore, the diversity of sources and the range of thematic keywords underscore the interdisciplinary and evolving nature of this research area.

3.2. Country-Level Contributions and Collaborations

The bibliometric analysis highlights the global nature of research on natural and biosorbent adsorbents for azo dye removal. A comprehensive visualization of country-level contributions (Figure 3) reveals that India, China, Iran, Türkiye, and Brazil are among the most productive countries in this field. The scientific production map indicates that Asian countries, particularly India and China, have made significant contributions, while European, African, and South American countries show varying degrees of participation. The geographical distribution of research activity underscores both regional priorities and global collaborative efforts aimed at addressing the challenges of azo dye contamination in wastewater.

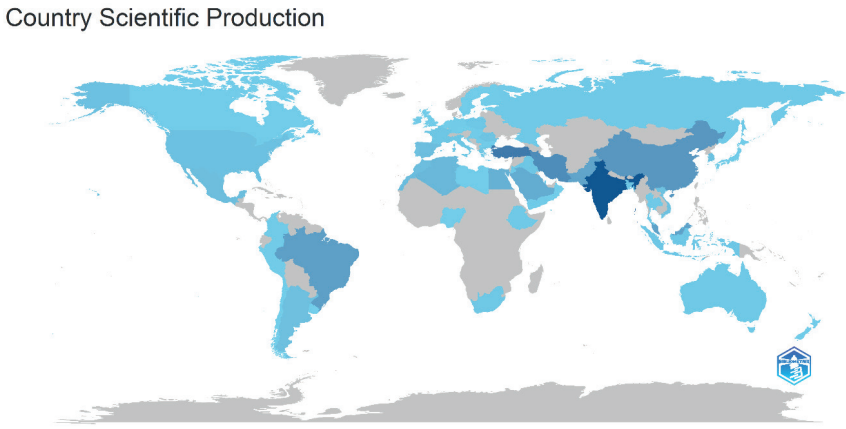

Figure 3. Global Distribution of Scientific Publications

The publication trends over time (Figure 4) reveal that India and China have exhibited the most rapid growth in research output since 2010, with Türkiye and Iran following closely. The continuous upward trajectory of these countries indicates sustained interest and investment in sustainable dye removal technologies. Notably, India has maintained a consistently high publication rate, while other countries such as Türkiye and Iran have demonstrated remarkable growth in recent years. This trend reflects increasing global recognition of the environmental hazards posed by azo dyes and the need for innovative treatment solutions.

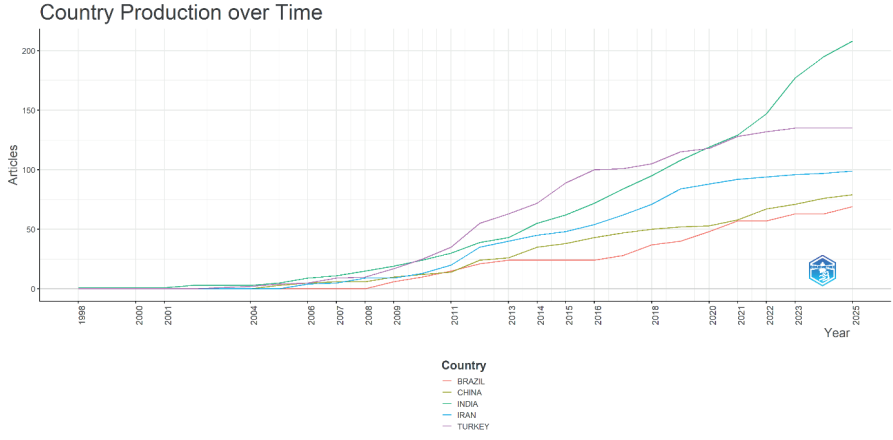

Figure 4. Temporal Trends in Publication Output by Country (1998–2025)

In terms of citation impact, Figure 5 illustrates that India leads in total citations, indicating a high level of academic influence and recognition for its contributions to this field. Malaysia, Ireland, Iran, and Türkiye also rank highly, suggesting that research originating from these countries has garnered substantial attention within the scientific community. The high citation rates for these countries highlight the global relevance and applicability of their findings in addressing azo dye pollution challenges.

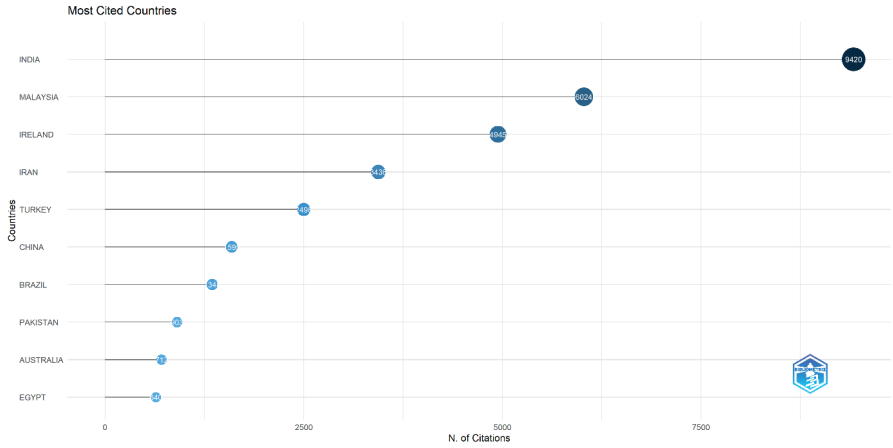

Figure 5. Most Cited Countries Based on Total Citation Counts

The analysis of corresponding author's countries (Figure 6) reveals that India, Türkiye, Iran, and China dominate both single-country publications (SCP) and multiple-country collaborations (MCP). This demonstrates the prominent role of these countries in leading research initiatives and fostering international partnerships. Countries like Brazil, Malaysia, and Pakistan also show significant contributions, indicating the diverse and international character of research collaborations in this domain.

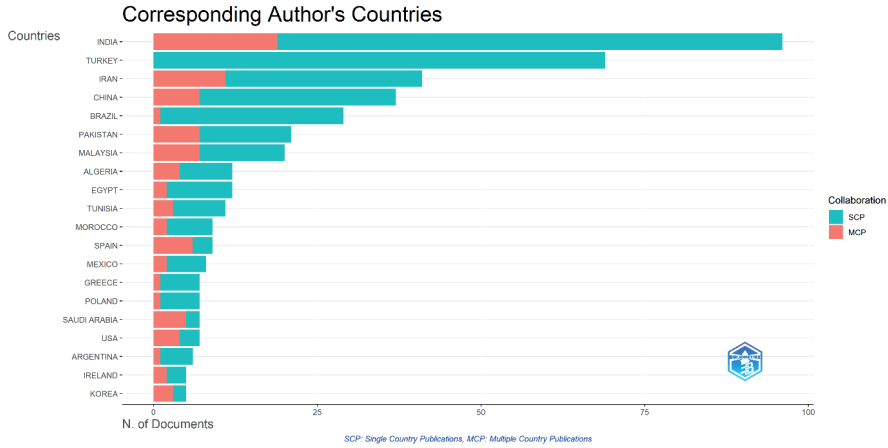

Figure 6. Distribution of Corresponding Author's Countries and Collaborative Patterns

The co-authorship network visualization (Figure 7) further emphasizes the interconnectedness of global research efforts. India emerges as a central node with extensive collaborations spanning across Asia, Europe, and Africa. Countries such as Iran, Türkiye, and China are also deeply embedded within this network, indicating their active participation in cross-national research partnerships. These collaborative patterns underscore the importance of cooperative research strategies to tackle complex environmental issues like azo dye pollution.

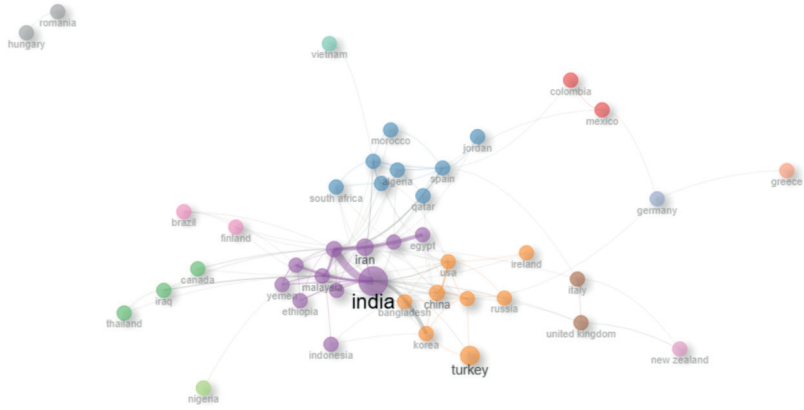

Figure 7. Map for Azo Dye Decolorization Studies

3.3. Institutional Contributions and Collaborations

The institutional-level analysis highlights key contributors to global research on natural and biosorbent adsorbents for azo dye decolorization. As shown in Figure 8, the Egyptian Knowledge Bank (EKB) and Eskisehir Osmangazi University emerge as the most prolific institutions, with 37 and 31 publications, respectively. Indian Institute of Technology (IIT System), University Sains Malaysia, and National Institute of Technology (NIT System) are also notable contributors, underscoring the active engagement of academic and research institutions from both developing and developed regions.

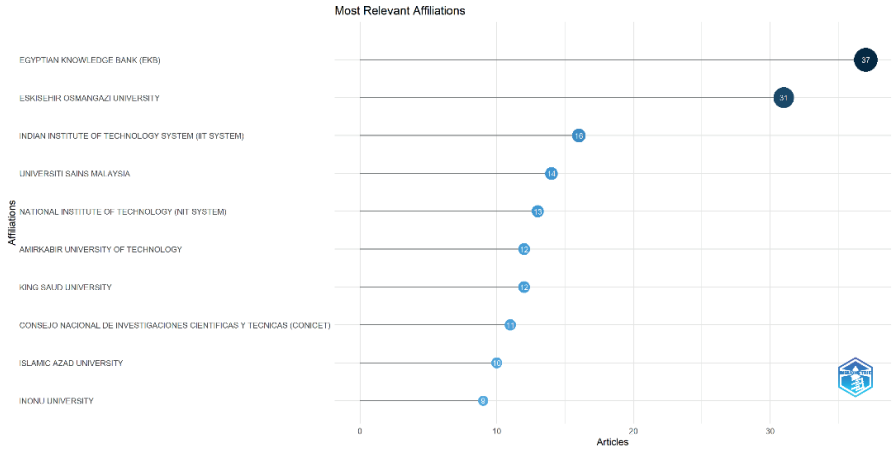

Figure 8. Most Prolific Research Institutions

The institutional collaboration network (Figure 9) further illustrates the interconnected nature of global research efforts. The IIT System (India) serves as a central hub, establishing extensive partnerships with institutions such as the Egyptian Knowledge Bank, Eskisehir Osmangazi University, and King Saud University. These collaborative networks indicate a strong commitment to addressing the global challenge of azo dye pollution through joint research initiatives and knowledge sharing.

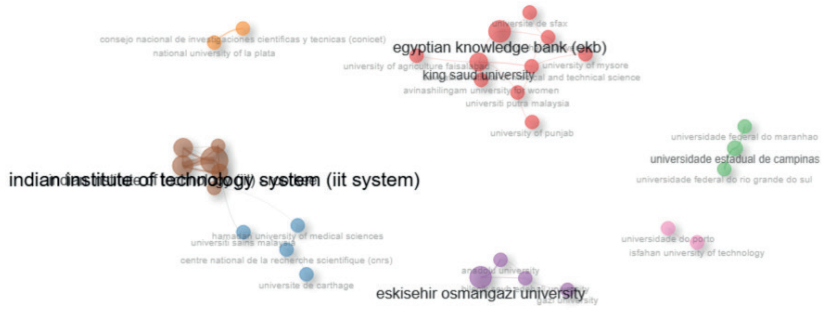

Figure 9. Institutional Collaboration Network for Azo Dye Decolorization Studies

3.4. Author-Level Contributions and Collaborations

The author-level analysis provides a detailed understanding of individual contributions, scholarly impact, and collaboration networks within the field of natural and biosorbent adsorbents for azo dye decolorization.

Figure 10 presents the Most Relevant Authors, highlighting the leading contributors based on the number of publications. Notably, Akar T, Arami M, and Mahmoodi NM emerge as the most prolific authors, reflecting their significant and sustained engagement in this research area. Other notable contributors include Agarwal S, Gupta VK, and Akar ST, underscoring the presence of both experienced and emerging researchers in the field. This distribution illustrates the diverse academic landscape contributing to advancements in azo dye remediation.

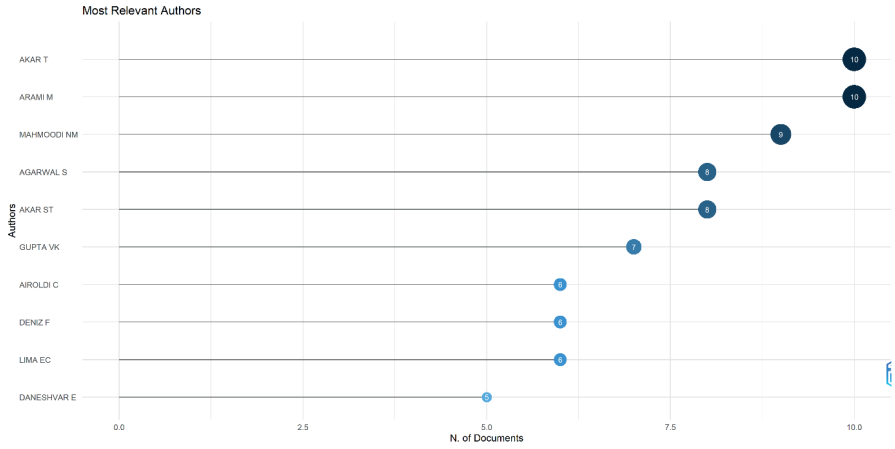

Figure 10. Most Relevant Authors

The Authors' Production Over Time (Figure 11) illustrates the publication trajectories of key researchers. Akar T, Arami M, and Mahmoodi NM demonstrate consistent publication activity since 2010, indicating long-term engagement with the field. Gupta VK shows a broad publication span with notable peaks, while other authors such as Agarwal S and Aioldi C contribute steadily. This trend analysis emphasizes both the longevity and consistency of contributions from leading researchers.

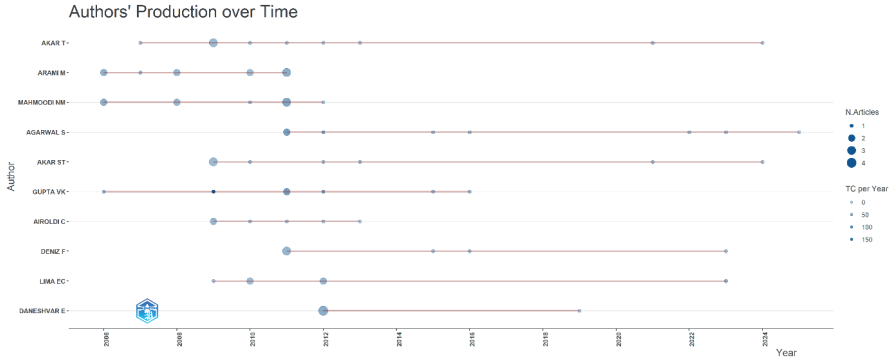

Figure 11. Temporal Trends in Publications of Leading Authors

3.5. Source-Level Analysis

The source-level analysis provides insights into the dissemination platforms that have played a pivotal role in advancing research on natural and biosorbent adsorbents for azo dye decolorization.

Figure 12 presents the Most Relevant Sources, identifying the top journals contributing to the field based on the number of publications. Desalination and Water Treatment emerges as the most prolific source with 41 publications, followed by Journal of Hazardous Materials (20 publications) and Chemical Engineering Journal (14 publications). Other notable sources include Bioresource Technology and Environmental Science and Pollution Research, reflecting a diverse array of journals covering environmental science, engineering, and sustainability domains. This distribution highlights the multidisciplinary nature of the research field and its alignment with global environmental priorities.

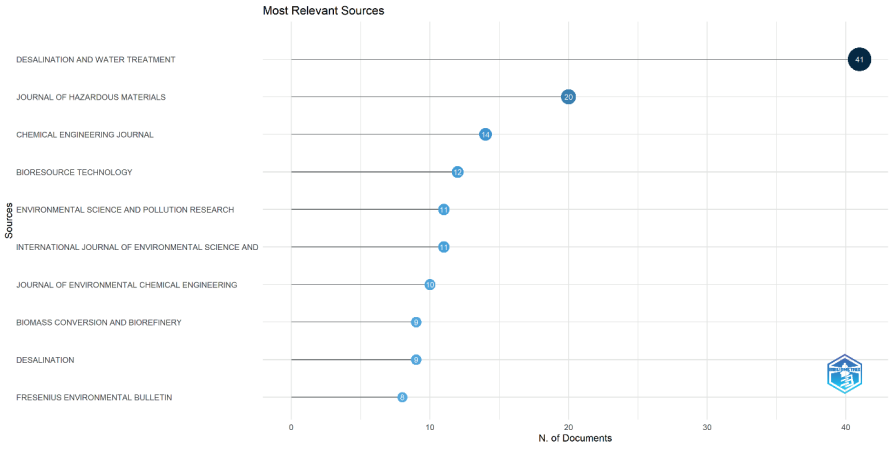

Figure 12. Most Relevant Journals

3.6. Citation Analysis

Citation metrics offer valuable insights into the scholarly influence and recognition of research on natural and biosorbent adsorbents for azo dye decolorization.

Figure 13 depicts the Average Citations per Year, illustrating the temporal trends of citation performance from 1998 to 2025. A striking peak is observed in 2001, where the average citation per publication exceeded 150, likely reflecting seminal works that laid the foundation for subsequent research in the field. However, a gradual decline in average citations is noted in later years, with modest fluctuations observed post-2010. This pattern suggests a maturation of the field, with foundational studies continuing to receive citations while more recent publications are gradually accumulating

impact. The overall trend underscores the importance of early pioneering research and highlights the ongoing relevance of contemporary studies.

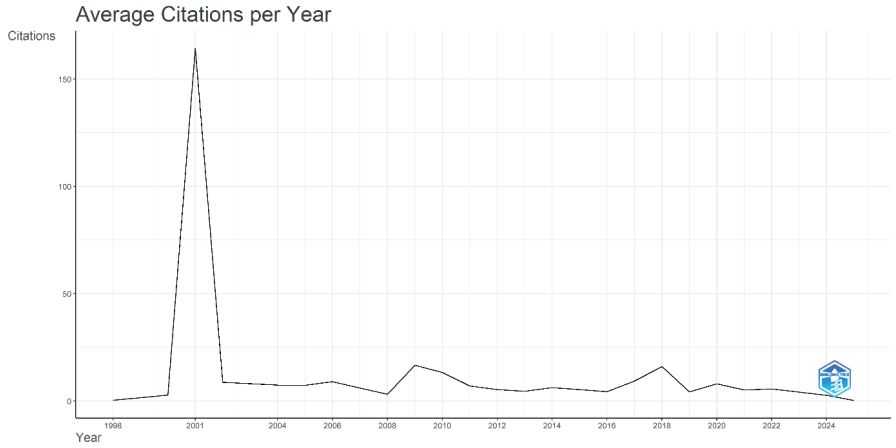

Figure 13. Average Citations per Year for Publications

3.7. Keyword Analysis and Thematic Trends

Keyword analysis provides critical insights into the thematic focus and conceptual evolution of research on natural and biosorbent adsorbents for azo dye decolorization.

Figure 14 presents the Co-occurrence Network of keywords, illustrating the relationships and thematic clusters within the field. Central keywords such as “adsorption,” “aqueous solution,” “removal,” “biosorption,” and “equilibrium” dominate the network, indicating their pivotal role in the literature. The clustering of terms into distinct thematic groups—one focused on adsorption and equilibrium dynamics, and another on dye-specific and material-related terms like “methylene blue” and “low-cost adsorbents”—reveals the interdisciplinary nature of this research field.

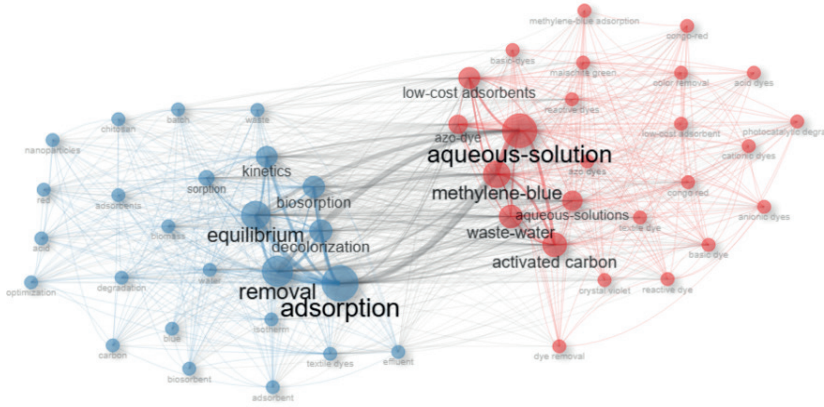

Figure 14. Keyword Co-occurrence Network

Thematic mapping (Figure 15) offers a nuanced perspective on the intellectual structure of the field. Thematic clusters such as "adsorption-removal-equilibrium" and "aqueous solution-methylene blue-activated carbon" appear in the lower-right quadrant, indicating well-developed and central themes. Clusters such as "natural adsorbents" and "reactive azo dyes" occupy less central positions, suggesting niche or emerging themes. This map not only categorizes existing research foci but also identifies areas for potential future exploration.

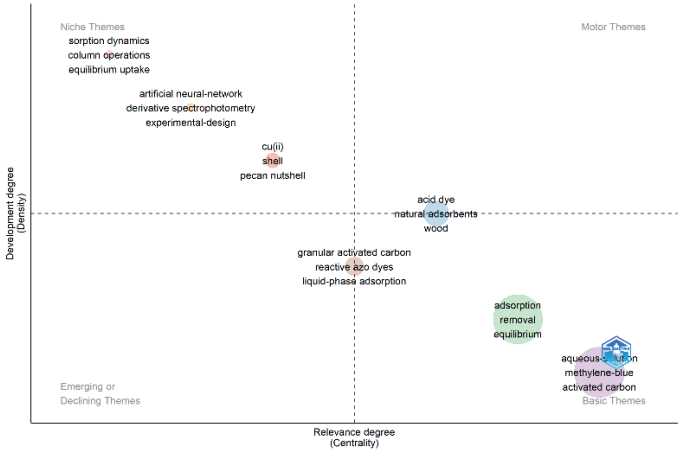

Figure 15. Thematic Map of Research Themes in Azo Dye Decolorization

The Three-Field Plot (Figure 16) visualizes the interconnections between keywords, journals, and countries. It reveals a strong linkage between key terms such as "adsorption" and "aqueous solution", high-impact journals like Desalination and Water Treatment and Environmental Science and Pollution Research, and leading contributing countries including India, Türkiye, and China. This visualization underscores the global and multidisciplinary character of the field.

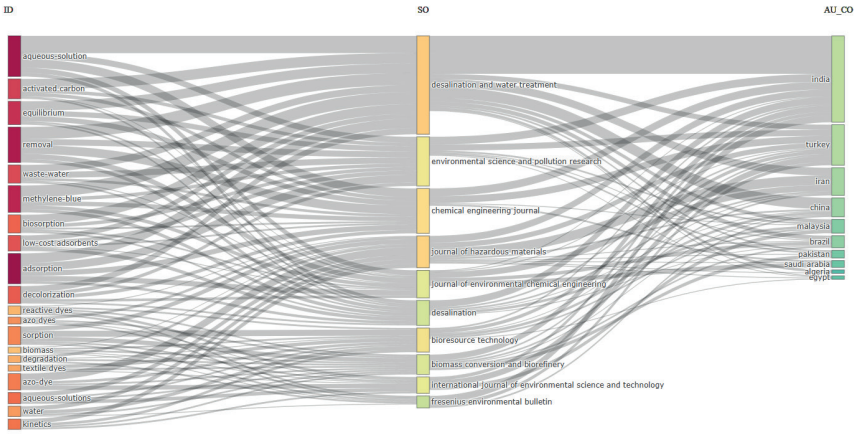

Figure 16. Three-Field Plot of Keywords, Journals, and Countries

The Trend Topics graph (Figure 17) depicts the temporal dynamics of research themes. Terms like "methylene-blue dye," "adsorption," "low-cost adsorbents," and "decolorization" show consistent growth in frequency over time, highlighting evolving research interests and the sustained importance of innovative treatment strategies. This trend analysis reflects the dynamic and expanding nature of the field.

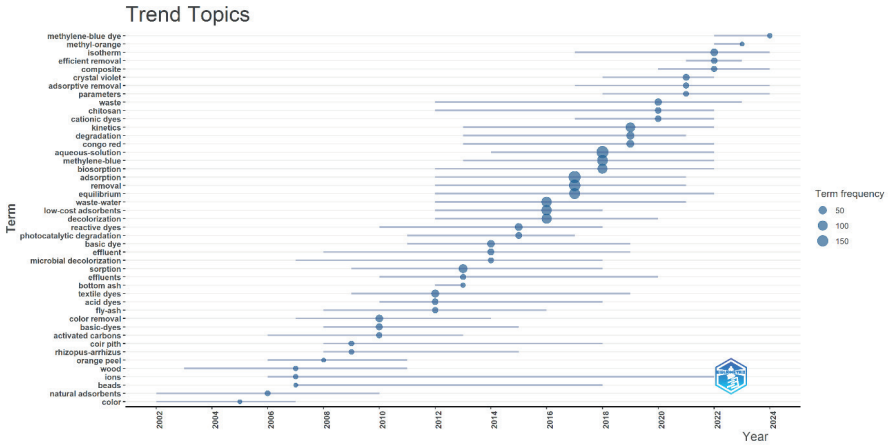

Figure 17. Temporal Trends of Key Research Topics

Finally, the Word Cloud (Figure 18) offers a visual summary of keyword prevalence, with terms like "adsorption," "aqueous solution," "methylene blue," "activated carbon," and "biosorption" standing out prominently. This visualization underscores the thematic richness and diversity within the research landscape.

Figure 18. Word Cloud of Most Frequent Keywords

The removal of azo dyes from wastewater represents a critical environmental challenge due to the dyes' persistence, complex molecular structures, and potential toxicity, including carcinogenic and mutagenic

effects (Mihai et al., 2024; Haoufazane et al., 2024). Recent advancements have focused on the utilization of plant-based natural adsorbents and mineral clay biosorbents as sustainable, cost-effective solutions for dye decolorization. These approaches leverage the inherent advantages of naturally abundant, low-cost materials with environmentally friendly characteristics, addressing both ecological concerns and circular economy principles (Qamar et al., 2024; Keshmiri-Naqab & Taghavijeloudar, 2024).

Plant-based natural adsorbents have garnered significant attention, with studies demonstrating the potential of agricultural waste products such as orange peel, sawdust, corncob, and peanut shells (Mihai et al., 2024; Keshmiri-Naqab & Taghavijeloudar, 2024). Notably, Zygophyllum gaetulum stems have shown removal efficiencies exceeding 97% for textile azo dyes like C.I. Direct Black 80 (Haoufazane et al., 2024), while sour cherry leaves achieved high adsorption capacities for methylene blue and crystal violet (Mosoarca et al., 2023). These adsorbents operate through mechanisms involving hydroxyl, carboxyl, and amino functional groups, enabling electrostatic interactions, hydrogen bonding, and π–π stacking with dye molecules (Qamar et al., 2024; Vialkova et al., 2024).

Mineral clay biosorbents—including kaolin, bentonite, and montmorillonite—are characterized by high surface area, porosity, and chemical stability, making them effective for dye removal (Reghioua et al., 2024; Khan et al., 2023). Innovations such as kaolin-cellulose composites and bentonite-based granular biosorbents have significantly enhanced adsorption capacities (Reghioua et al., 2024; Keshmiri-Naqab & Taghavijeloudar, 2024). Moreover, the development of clay nanocomposites and modified clays has improved adsorptive performance due to increased surface reactivity and porosity (Ciğeroğlu et al., 2024; Bosu et al., 2023). Despite these advancements, challenges related to regeneration, disposal, and cost-effectiveness remain areas for future research (El-Habacha et al., 2023).

The bibliometric analysis of the current literature indicates a global and collaborative effort in this field. Research themes have evolved from basic adsorption studies to more sophisticated developments involving nanocomposites and hybrid materials (Ciğeroğlu et al., 2024; Khan et al., 2023). Regional contributions, particularly from Asia, the Middle East, and Europe, reflect both the availability of plant and clay resources and the pressing need for sustainable wastewater treatment solutions (Mihai et al., 2024; Haoufazane et al., 2024). Future research directions include optimizing synthesis methods for biosorbents, improving long-term stability and recyclability, and integrating machine learning models for performance prediction and system optimization (Bosu et al., 2023; Khan et al., 2023).

To further illustrate these findings, Table 2 provides a comparative summary of various plant-based and clay biosorbents, highlighting their maximum adsorption capacities and the target dyes. This table consolidates key performance data from recent studies and serves as a reference point for evaluating the effectiveness of different adsorbent materials in azo dye removal.

Table 2. Comparative Analysis of Adsorbent Materials for Azo Dye Removal

Adsorbent Material	Maximum Adsorption Capacity (mg/g)	Target Dye	Citation
Orange Peel Waste and Biochar	15.72–74.62	Alizarin Yellow R	(Mihai et al., 2024)
Bentonite-Sawdust-Corncob Granular	135.22	Acid Orange 7	(Keshmiri-Naqab & Taghavijeloudar, 2024)
Zygophyllum gaetulum Stems	97.08%	C.I. Direct Black 80	(Haoufazane et al., 2024)
Kaolin-Cellulose (KA/CEL)	291.5 (MB), 130.7 (CR)	Methylene Blue, Congo Red	(Reghioua et al., 2024)
Sour Cherry Leaves	168.6 (MB), 524.1 (CV)	Methylene Blue, Crystal Violet	(Mosoarca et al., 2023)
Bentonite Clay Nanocomposites	909.09	Synthetic Dyes	(Ciğeroğlu et al., 2024)
Modified Bentonite	179	Heavy Metals and Dyes	(El-Habacha et al., 2023)

In summary, plant-based and mineral clay biosorbents present promising avenues for the sustainable removal of azo dyes from wastewater. Their application not only addresses environmental challenges but also promotes resource valorization and circular economy principles. The continued evolution of this research field is essential for advancing effective, scalable, and eco-friendly solutions to global water pollution challenges (Qamar et al., 2024; Mihai et al., 2024).

4. Conclusion

This study represents the first comprehensive assessment of natural and biosorbent adsorbents for azo dye removal. Indeed, this work constitutes the first systematic application of bibliometric methods to evaluate research progress and thematic evolution in this area. The analysis encompasses 489 publications indexed in the WoS between 1998 and 2025. The findings reveal a steady annual increase in publication output (11.3% growth rate)

and a robust average citation impact (78.74 citations per document), highlighting the sustained and growing interest in sustainable wastewater treatment technologies.

Notably, India, China, Iran, Türkiye, and Brazil are the leading contributors in terms of publication volume. In terms of institutions, key contributors include the Egyptian Knowledge Bank, Eskisehir Osmangazi University, Indian Institute of Technology (IIT System), Universiti Sains Malaysia, and National Institute of Technology (NIT System), which are recognized for their prolific research efforts and extensive collaborations. Among the researchers, Akar T, Arami M, and Mahmoodi NM have the highest number of publications and citations, underscoring their central role in advancing this field. The primary publications have appeared in journals such as *Desalination and Water Treatment*, *Journal of Hazardous Materials*, and *Chemical Engineering Journal*, reflecting an interdisciplinary trend that spans Environmental Science, Chemical Engineering, Materials Science, and Sustainability Research.

The analysis of keywords indicates the main areas of research focus: (1) synthesis, characterization, and performance evaluation of natural and biosorbent materials for dye adsorption, (2) investigation of adsorption mechanisms including isotherms and kinetics, and (3) the development of hybrid treatment strategies that combine physical, chemical, and biological processes for enhanced dye removal efficiency. The research predominantly revolves around the application of plant-based adsorbents (e.g., agricultural waste, biomass) and mineral clays (e.g., kaolin, bentonite) for the decolorization of azo dyes, with a growing emphasis on nanocomposites and modified adsorbents to improve performance.

Despite significant advancements in the field of natural and biosorbent adsorbents for azo dye removal, several challenges remain unresolved. These include issues related to adsorbent regeneration and reusability, scalability for industrial applications, and the need for techno-economic assessments to ensure cost-effectiveness. Additionally, the integration of advanced technologies such as machine learning for performance modeling and the standardization of adsorption process evaluation are key areas for future research.

The findings of this study provide valuable insights for material scientists, environmental engineers, policymakers, and industries engaged in sustainable wastewater treatment, offering a solid foundation for further innovation and interdisciplinary collaboration in addressing one of the most pressing environmental challenges of our time.

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