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Review Article

Bibliometric Analysis of Water Pollution Research: Focus on Industry Impacts

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Abstract

Water pollution is a pressing global issue, particularly in regions heavily impacted by industrialization. This results in aquatic ecosystem degradation, biodiversity loss, and significant health risks from waterborne diseases and prolonged exposure to toxic pollutants. Industrial waste is a key contributor, highlighting the urgency of effective mitigation strategies. This study aimed to analyze research trends in industrial water pollution, identify knowledge gaps, and provide actionable insights for policymakers. A bibliometric analysis and literature review were conducted on 2,523 articles published between 2015 and 2024 using R software and the Biblioshiny interface. In addition, 30 highly cited articles were reviewed in-depth to explore dominant themes and advancements. The findings show a marked increase in research output, with China as the leading contributor. Key topics include the impact of industrial effluents, innovative water treatment technologies, and regulatory measures. However, significant gaps remain, particularly in interdisciplinary approaches and research on developing countries, such as Indonesia. This study recommends advancing scalable, cost-effective hybrid technologies, fostering interdisciplinary collaboration, and promoting public awareness initiatives. This study highlights the need to integrate technological, social, and policy dimensions to address industrial water pollution effectively, offering a pathway for sustainable solutions and future research directions.

Keywords: Water pollution research; bibliometric analysis; biblioshiny

1. Introduction

Water pollution is a pressing environmental issue worldwide, including in Indonesia. This contamination occurs when harmful substances, both natural and anthropogenic, enter water bodies such as rivers, lakes, and oceans, leading to altered water quality and posing a threat to ecosystems and human health (Podlasek et al., 2024; Singh et al., 2024). The impact of water pollution is not only local but extends beyond borders, affecting water resources that are vital for the sustenance of millions of people. As a global environmental challenge, water pollution impacts various regions differently, with specific concerns in each region. In Indonesia, for instance, rapid industrialization and population growth have exacerbated the problem, resulting in the contamination of freshwater resources that are crucial for both domestic and industrial use. Therefore, addressing water pollution requires a comprehensive understanding of its sources, impact, and potential solutions.

Various factors contribute to water pollution, including industrial waste (Garg et al., 2022; Khanam et al., 2022), domestic waste (Abdallah et al., 2022; Widyarani et al., 2022), the use of chemical fertilizers in agriculture (Bijay-Singh and Craswell, 2021; Jwaideh et al., 2022), and mining activities (Mlewa et al., 2023; Sharifi et al., 2023). Industrial waste often contains toxic chemicals and heavy metals that are harmful to aquatic life and human health. These pollutants degrade water quality and disrupt the ecosystems. The discharge of untreated industrial waste into water bodies is a major contributor to water pollution. Factories producing chemicals, textiles, and food products often release large amounts of pollutants into rivers and lakes, including hazardous substances such as cadmium, mercury, and lead. These toxic chemicals can accumulate in the food chain, leading to severe ecological and health consequences for humans and animals.

Efforts to mitigate water pollution have been a significant focus of recent research, with methods such as adsorption, coagulation, and advanced oxidation processes emerging as effective approaches. Adsorption has been extensively studied using materials such as activated carbon and biochar for the removal of heavy metals and organic pollutants from water (Qiu et al., 2021; Viotti et al., 2024). Coagulation techniques, often combined with flocculation, have proven effective in reducing turbidity and removing contaminants from wastewater (Bratby, 2016). Other advanced methods, such as membrane filtration and photocatalysis, have shown promising results for treating industrial wastewater (Mansor et al., 2024; Thanh et al., 2024). These studies demonstrate the potential of innovative technologies to address water pollution and restore water quality, particularly in industrially impacted regions.

The impacts of water pollution are extensive, ranging from damage to aquatic ecosystems to severe health issues for communities dependent on contaminated water sources. Polluted water can lead to the death of aquatic organisms, loss of biodiversity, and destruction of vital ecosystems such as wetlands. For human populations, waterborne diseases, such as cholera and dysentery, can result from drinking contaminated water, whereas long-term exposure to heavy metals and chemicals can cause chronic health conditions. These health issues are particularly critical in developing countries such as Indonesia, where access to clean water remains a significant challenge in rural and industrial areas.

Several studies have explored the impact of industry on water pollution. In recent decades, many studies have examined the relationship between industrial activities and water pollution, including research on eutrophication caused by the use of chemical fertilizers and the disposal of hazardous waste by the manufacturing and mining sectors. For example, Rabalais et al. (2009) studied eutrophication in bays and its impact on ecosystems, which is aligned with the study by Bonsdorff (2021), who explored the effects of excess nitrogen and phosphorus on aquatic environments. Rathore et al. (2016) stated that eutrophication leads to a decline in oxygen levels, making ecosystems unhealthy. These studies provide valuable insights into how industries contribute to water pollution and its impact on human health and the environment. The research trend indicates a growing interest in this topic, reflecting the urgency of comprehensively understanding and addressing water pollution.

Bibliometric analysis offers a robust methodological approach to address this issue. This enables the systematic evaluation of research trends, collaboration patterns, and the impact of scholarly contributions in specific fields (Baas et al., 2020; Sakib et al., 2024). By analyzing citation data, publication trends, and author networks, bibliometric analysis provides insights into how research has evolved and its effectiveness in addressing pressing issues, such as water pollution. However, while bibliometric analysis has been widely applied in various disciplines, its application in studying industrial contributions to water pollution remains unexplored. Existing studies often focus on identifying dominant themes or productive authors, but few have delved into how these findings can inform practical solutions or guide future research directions. This represents a significant gap, particularly in the context of developing countries such as Indonesia, where evidence-based strategies are crucial for tackling water pollution and achieving sustainable development goals (SDGs).

The use of advanced tools, such as Biblioshiny, an interactive interface of the "bibliometrix" R package, enhances the effectiveness of bibliometric analyses. Combined with comprehensive databases such as Scopus, Biblioshiny facilitates the exploration of publication patterns, co-authorship networks, and keyword trends, enabling researchers to identify underexplored areas and emerging themes. While these tools are instrumental in synthesizing existing knowledge, the novelty of their application lies in integrating bibliometric findings with actionable recommendations for addressing environmental issues. This study seeks to bridge this gap by employing bibliometric analysis to systematically evaluate research on industrial water pollution, focusing on its implications for environmental sustainability and public health in Indonesia. Therefore, the objectives of this article are threefold: (1) to analyze research trends and patterns in industrial water pollution studies using bibliometric analysis; (2) to identify knowledge gaps and underexplored areas that require further investigation; and (3) to provide actionable insights for policymakers and practitioners to develop evidence-based strategies for mitigating water pollution and achieving sustainable development goals. By addressing these objectives, this study aims to contribute to a more comprehensive understanding of water pollution and its mitigation, particularly in the context of Indonesia's environmental challenges.

Unlike previous studies that primarily focus on identifying dominant themes or authors in water pollution research, this study integrates bibliometric analysis with actionable recommendations, particularly addressing underexplored regions like Indonesia and emphasizing interdisciplinary approaches.

2. Methods

The method used in this study is qualitative with a literature study approach. The literature search was conducted using the Scopus database. The selection of this database is justified by its extensive coverage, the large number of publishers, and its status as a primary source for indexing scientific articles and various types of papers worldwide (Jabeen et al., 2021; Liu and Avello, 2021; Mongeon and Paul-Hus, 2016). Moreover, this database allows for searches across diverse fields, either comprehensively or by restricting to titles, abstracts, and author keywords along with predefined search terms (Linnenluecke et al., 2019; Sharif et al., 2019). Additionally, Scopus provides the largest peer-reviewed abstract and citation database, offering high-quality, reliable coverage with complete data for every reference (Zanjirchi et al., 2019).

The literature search followed specific protocols. These protocols outlined various aspects, including search terms, databases used, exclusion criteria, types of publications considered, and the timeframe for the research or publication of the specified literature. The search protocol involved using the query TITLE-ABS-KEY ("Water Pollution" OR "Water Contamination" AND "Industr* Pollution" OR "Industr* Wastewater" OR "Chem* Industr*" OR "Industrial Effluent*"). Several limitations were applied: papers selected were only in English; the timeframe was set from 2015 to 2024; and document types were limited to articles, reviews, conference papers, and book chapters. Keywords were restricted to "Water Pollution," "Water Pollutant," "Water Pollutants, Chemical," "Industrial Wastewaters," "Waste Water," "Wastewater Treatment," "Environmental Pollutants," "Environmental Pollutions," "Industrial Water Treatment," and "Waste Water Management." After applying the final inclusion criteria, the search equation “Water Pollution” OR “Water Contamination” in the Scopus database yielded an initial total of 74,451 publications. By narrowing the focus to studies that specifically address water pollution caused by industrial activities, the results were reduced to 2,523 documents. The literature data was retrieved on December 24, 2024. After obtaining the documents from the database, the 2,523 selected papers were exported to the “BibTeX” format and imported into the R application. For bibliometric analysis, the R tool was utilized, which is an open-source platform designed for scientific mapping and is implemented using the R programming language (Aria and Cuccurullo, 2017). The selection of this software is due to its effectiveness and utility in bibliometric analysis tools (Qin et al., 2022). Bibliometrix, an innovative open-source tool, facilitates detailed bibliometric analyses and scientific mapping using the R programming language (Aria and Cuccurullo, 2017). This study employed the 'Biblioshiny for Bibliometrix' tool from R for conducting bibliometric analysis. Biblioshiny enables direct web-based visual analysis of data and facilitates the exploration of publication trends, co-authorship networks, and keyword occurrences (Yao et al., 2024).

An in-depth analysis was conducted on the 30 articles with the highest Cited Total Per Year (CTPY). By limiting the analysis to the top 30 articles, this study can focus more on exploring the most widely accepted methodological trends, significant innovations, and the real-world impact of the research on scientific development. This approach also allows the researchers to identify and evaluate key contributions in industrial waste management, providing a comprehensive understanding of both theoretical and practical advancements in this field. Figure 1 illustrates the steps involved in data collection and processing analysis retrieved from the Scopus database.

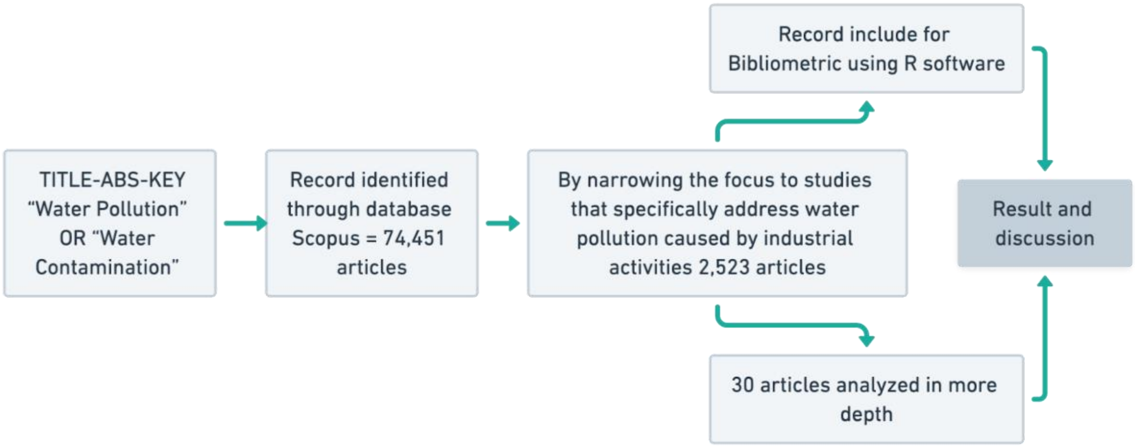

Figure 1. Flowchart of data collection, data analysis, and data visualization

Using these tools in this study supports achieving its objectives by identifying and analyzing the evolution of water pollution literature. Moreover, these tools assist in identifying the most productive authors, journals, countries, and organizations in the field of water pollution research. Additionally, the tools aid in establishing bibliographic relationships among authors, journals, and countries; exploring keyword co-occurrences; and generating thematic analyses of water pollution publications.

This study is motivated by a three-step analytical strategy (Qin et al., 2022), which includes descriptive analysis, bibliometric network analysis, and in-depth qualitative analysis (content analysis) of subsequent performance analysis and academic discourse in the field of water pollution research. Initially, the study provides a descriptive analysis of information and trends in water pollution literature. It begins by examining performance metrics, focus areas, and visualizations related to water pollution studies. Valuable insights are derived from publication volume, publication years, authors, journals, countries, keywords, citations, and various impact measurements.

Subsequently, through bibliometric network analysis, the study emphasizes the relationships among these components in water pollution publications. To achieve this, the study considers the co-citation of journals, authors, countries, and keyword co-occurrence. This analysis helps reveal co-authorship and co-word analyses, effectively exploring the global knowledge structure and its networks. Finally, the study conducts an in-depth qualitative analysis that systematically reviews the literature to identify various determinants and impacts of water pollution, methods employed, and influential factors discussed across the literature.

3. Result and Discussion

3.1. Bibliometric Results

3.1.1. Overview of scientific production

A bibliometric analysis encompassing 2,523 publications obtained from the Scopus database reveals scientific research on water pollution caused by industrial activities from 2015 to 2024. These publications include various document types, such as articles, reviews, conference papers, and book chapters, each contributing to a deeper understanding of water pollution. The focus lies on identifying the primary causes of pollution from industrial waste and examining its impacts on the environment and public health. Furthermore, these documents provide not only insights into pollution sources but also strategies and practical solutions to address the issue. As such, the publications are highly relevant to real-world conditions, offering comprehensive analyses and actionable recommendations for mitigating the effects of water pollution. Collectively, these studies serve as valuable resources for researchers, policymakers, and practitioners aiming to effectively address the challenges of industrial waste-induced water pollution. The development of these publications is presented in Table 1, which highlights a notable upward trend in the number of studies on water pollution caused by industrial activities between 2015 and 2024.

Table 1. Annual scientific production

Year	Articles
2015	154
2016	174
2017	180
2018	185
2019	209
2020	221
2021	292
2022	327
2023	358
2024	423

The bibliometric analysis reveals a steady increase in the number of publications on water pollution caused by industrial activities from 2015 to 2024. In 2015, 154 articles were published, followed by a gradual rise to 174 in 2016, 180 in 2017, and 185 in 2018. A significant increase began in 2019 with 209 articles, climbing further to 221 in 2020. The most substantial growth occurred in 2021, with 292 articles published, continuing with 327 in 2022, 358 in 2023, and peaking at 423 articles in 2024. This notable growth aligns with heightened global attention to sustainability and environmental issues, driven by international initiatives like the Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production).

The upward trend from 2019 to 2024 reflects a global paradigm shift toward environmental research. For instance, Khan et al. (2022) observed rising awareness in academia regarding the impacts of industrial pollutants, such as heavy metals and toxic chemicals. Similarly, Aria & Cuccurullo, (2017) highlighted the role of advancements in bibliometric analysis tools in facilitating literature identification and analysis, leading to an increase in publications. The sharp rise in 2021 may also be attributed to the COVID-19 pandemic, which heightened global awareness of the link between public health and environmental quality. Usman & Ho (2021) noted that the pandemic motivated greater research into environmental impacts, including water pollution, as clean environments were recognized as critical for human health.

Additionally, international policies like the Paris Agreement and stricter environmental regulations in developing countries contributed to this trend (Olmstead and Zheng, 2021; S. Wang et al., 2021). Technological advancements, such as computational modeling, big data analytics, and improved laboratory methodologies, have further enabled comprehensive exploration of water pollution issues, particularly in wastewater treatment technologies (Abdallah et al., 2022; Belete et al., 2023). However, despite the positive trend, challenges remain. Mongeon & Paul-Hus, (2016) pointed out a persistent gap between academic research and field implementation. Many studies focus on problem identification, while the practical adoption of solutions by industries remains limited. Furthermore, most research is concentrated in developed countries, leaving developing nations, such as Indonesia—often the most affected by severe water pollution underrepresented.

To address these gaps, future research should prioritize developing cost-effective and accessible wastewater treatment technologies tailored to developing countries. Additionally, collecting localized data and integrating sustainability principles with community-based approaches is essential to ensure inclusive and effective solutions. The increasing number of publications represents a significant opportunity to generate impactful outcomes that mitigate industrial water pollution. However, bridging the gap between research and policy implementation remains critical for achieving tangible results. Lastly, the fluctuating average citations per article highlights the need to ensure not only the quantity but also the quality and relevance of research in this field.

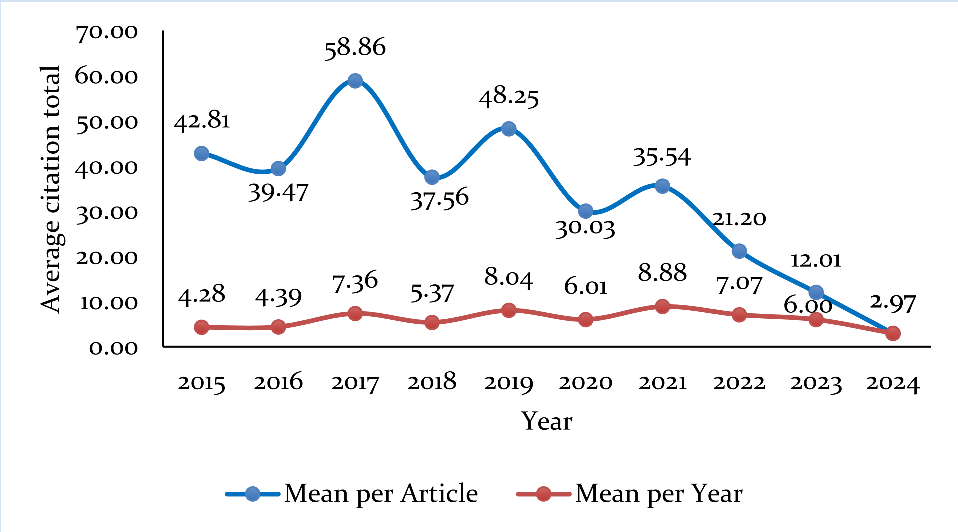

Figure 2. Average citations total per article and average citations per year from 2015 to 2024

Based on the data in Figure 2, the citation trends related to industrial water pollution exhibit a fluctuating pattern over the years. The Mean Total Citation per Article peaked in 2017 at 58.86, followed by a gradual decline in subsequent years, reaching its lowest point in 2024 at 2.97. This trend indicates that although the number of publications increased significantly—from 154 articles in 2015 to 423 in 2024—the quality or impact of these articles, as measured by citations, did not increase proportionally. The Mean Total Citation per Year also varied, peaking in 2021 at 8.88, suggesting that certain years saw research that was more relevant or gained more attention from the scientific community. This analysis highlights that an increase in publication quantity does not necessarily correspond to higher research impact or relevance. The declining average citations per article in recent years may reflect challenges in maintaining research quality and influence amid the surge in publication volume. Previous studies, such as Zhang et al. (2024), noted that stricter environmental regulations in developing countries have driven more research addressing industrial impacts on the environment. However, the rise in publication numbers might also signify a more competitive field, making it harder for individual articles to gain significant attention.

To address this issue, strategic measures are needed to ensure research quality by focusing on relevant, innovative, and impactful topics. International collaborations and publishing in high-impact journals can enhance the visibility and influence of research. Additionally, researchers should actively disseminate their findings through conferences, social media, and scientific forums to increase accessibility and citation opportunities. By implementing these strategies, future citation trends are expected to reflect not only an increase in publication quantity but also improved research quality and impact.

3.1.2. Sources of Publications

The number of documents published by each journal related to the theme of water pollution is depicted in Figure 3, using blue bar charts where darker shades represent higher publication quantities and greater relevance to the topic. The Most Relevant Sources data highlight the journals most significant in addressing industrial water pollution research from 2015 to 2024. *Science of the Total Environment* leads with the highest contribution of 131 articles, followed by the *Journal of Chemical Technology and Biotechnology* with 112 articles and *Chemosphere* with 90 articles. Other relevant journals include *Environmental Monitoring and Assessment* (72 articles), *Environmental Science and Pollution Research* (61 articles), and the *Journal of Cleaner Production* (49 articles).

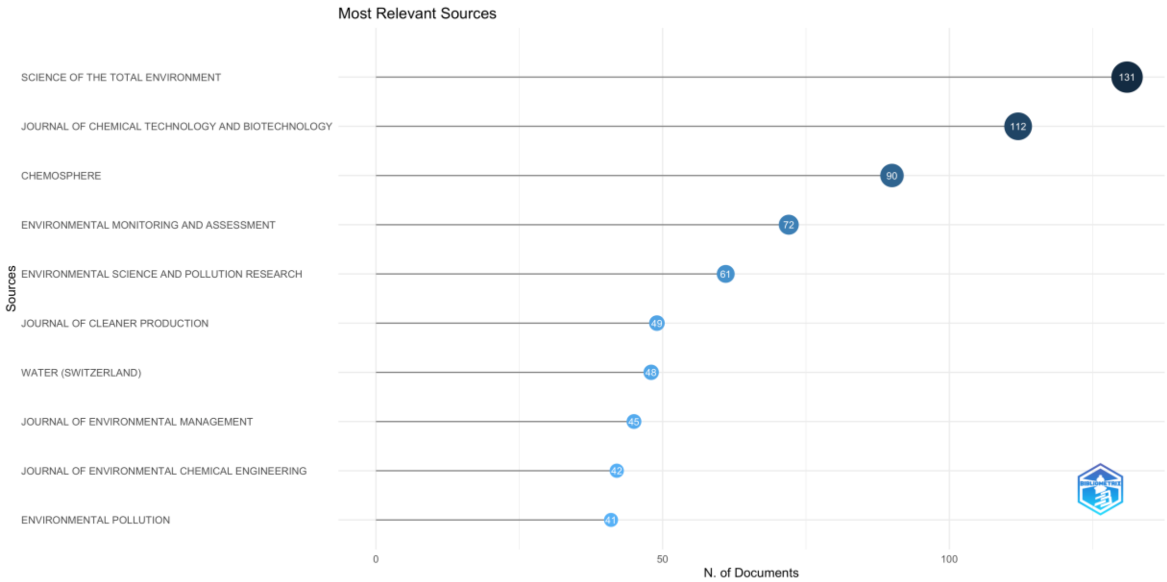

Figure. 3. Most relevant sources

Among the top ten most relevant journals, *Science of the Total Environment* ranks first, publishing the most research on this topic. This Q1-indexed journal, published by Elsevier in the Netherlands, is described as "an international journal for scientific research into the environment and its relationship with humankind," covering fields such as environmental chemistry, engineering, pollution, and waste management. The *Journal of Chemical Technology and Biotechnology (JCTB)*, published by John Wiley & Sons Ltd, focuses on the application of scientific and technological advancements in chemical and biological technologies to promote economically and environmentally sustainable industrial processes. Similarly, *Chemosphere* is a multidisciplinary journal dedicated to research on chemicals in the environment, addressing various aspects of pollution across the biosphere, hydrosphere, lithosphere, and atmosphere.

The high number of publications in these journals reflects the urgent demand for practical solutions and in-depth research on industrial water pollution. These journals, with their broad scope, international readership, and strong reputations in environmental science, dominate the list. Publishing in high-impact journals like these can significantly enhance the visibility of research and accelerate the translation of findings into policy and industrial practices. Understanding the countries leading in publications on industrial water pollution is equally crucial. It provides insights into global contributions to this research area and identifies nations prioritizing environmental issues and innovative solutions.

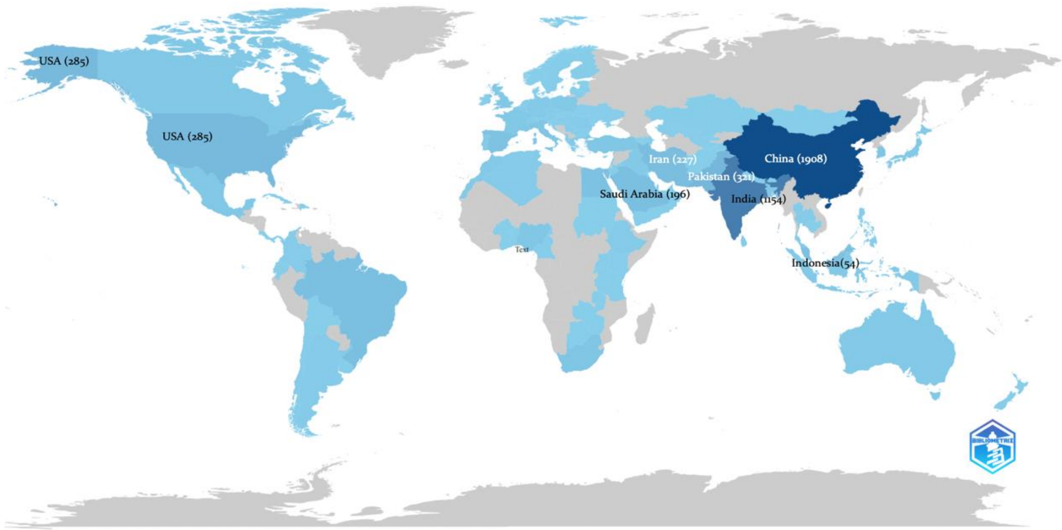

Figure 4. Countries scientific production

Based on Figure 4, China ranks as the country with the highest number of publications related to industrial water pollution, with a total of 1,908 publications. This reflects China's significant focus on the issue, considering its massive scale of industrialization and its environmental impacts (Ahmed et al., 2022; Fan and Fang, 2020; Yattara, 2021). India holds the second position with 1,154 publications, highlighting its strong concern for water pollution, particularly given the extensive areas in India affected by industrial activities and its high population density. Meanwhile, other countries such as Pakistan, the United States, Iran, and Saudi Arabia contributed 321, 285, 227, and 196 publications, respectively. Although these numbers are smaller compared to China and India, they indicate that water pollution remains a critical research focus in these nations. On the other hand, Indonesia is ranked 26th, with only 54 publications from 2015 to 2024.

This result suggests that attention to water pollution research in Indonesia remains relatively low compared to other countries. Several factors may contribute to this, such as limited research resources, lack of international collaboration, or a research focus dispersed across various other fields. In contrast, countries with higher publication numbers typically exhibit massive industrialization, an urgent need for pollution mitigation, and substantial funding support for environmental research. To increase its contribution to water pollution research, Indonesia needs to strengthen funding in this field and encourage more collaboration with countries producing higher publication volumes. Moreover, raising awareness among the public and industry players about the impacts of water pollution is an essential step (Mishal et al., 2017; Pongsophon, 2024). Producing a greater quantity of high-quality research can also serve as a basis for developing more effective policies to address water pollution issues at the national level. By implementing these measures, Indonesia could improve its ranking and demonstrate a stronger commitment to environmental preservation and the sustainability of water resources.

3.1.3. Authors' Contributions and Patterns

The Most Relevant Authors (Table 2) highlights researchers actively contributing to the study of water pollution caused by industrial waste.

Table 2. Most relevant authors

Authors	Articles	Articles Fractionalized
WANG Y	50	9.26
ZHANG Y	50	7.87
LIU Y	47	8.36
LI Y	44	8.40

Authors	Articles	Articles Fractionalized
WANG J	37	5.39
WANG S	32	4.74
LI J	31	5.16
LI X	31	4.49
ZHANG H	30	4.62
CHEN Y	29	4.72

Based on the Most Relevant Authors' data for research on industrial water pollution, names such as Wang Y, Zhang Y, and Liu Y emerge as major contributors to publications between 2015 and 2024. Both Wang Y and Zhang Y have authored 50 articles each, reflecting significant contributions to this topic. However, when assessed through the lens of Articles Fractionalized, which accounts for each author's contribution based on the level of collaboration within each publication, the values decrease to 9.26 and 7.87, respectively. This indicates that while their productivity is high, these publications often involve multi-author collaborations. This trend highlights that industrial water pollution is a highly complex issue requiring multidisciplinary collaboration to develop more holistic solutions. As noted in previous studies, such as Tu et al. (2024), environmental research often necessitates collaboration to understand and mitigate pollution impacts from multiple perspectives. Moving forward, the scientific community needs to continue expanding international collaboration networks, particularly by engaging more researchers from countries directly affected by industrial water pollution. Furthermore, governments and academic institutions need to provide greater support in the form of funding and collaborative platforms to enhance the quality and impact of related research. These efforts will accelerate the development of more effective solutions for addressing industrial water pollution, benefiting both the scientific community and affected regions.

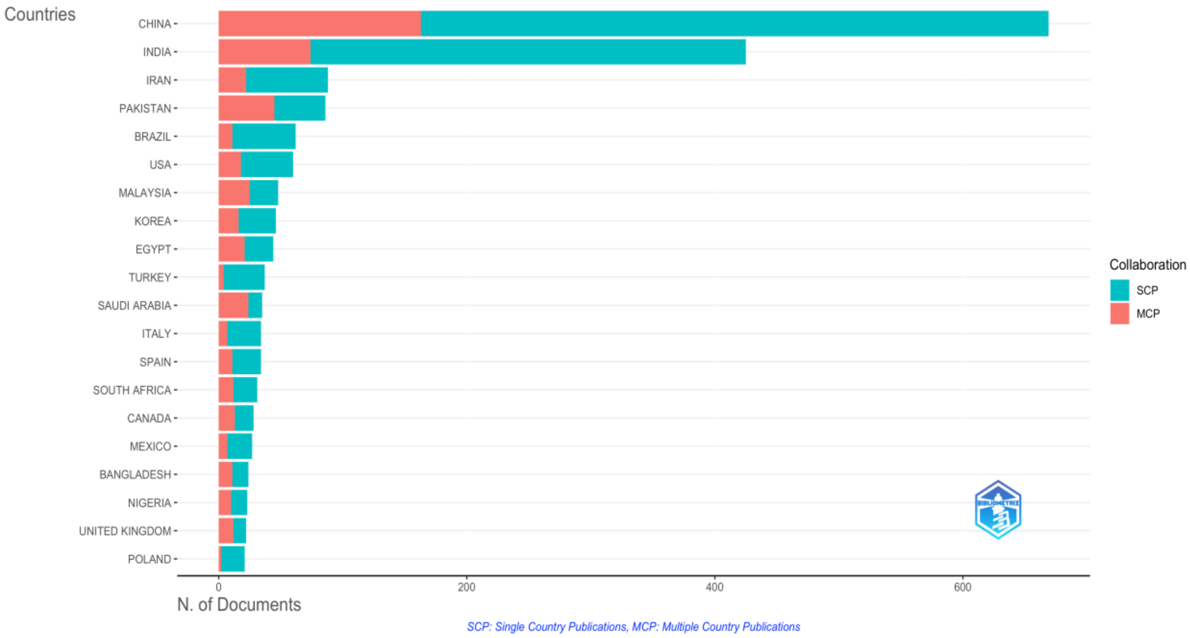

Figure 5. Corresponding Author's countries

Figure 5 illustrates the contributions of various countries to research on industrial water pollution from 2015 to 2024, categorized into Single Country Publications (SCP) and Multiple Country Publications (MCP). China stands out as the leading contributor, predominantly through SCP, highlighting a focus on domestic research. This aligns with findings from Wang et al. (2021) and Qin & Wang (2023), who emphasized that China's rapid industrialization has resulted in significant water pollution, driving localized research efforts to address these challenges. India and Iran also show substantial SCP contributions, indicating that research in these countries primarily adopts a national approach. In contrast, countries such as Malaysia, Egypt, and Bangladesh exhibit a more balanced distribution between SCP and MCP, reflecting an equal emphasis on domestic and international collaborations. Meanwhile, nations like Saudi Arabia and the United Kingdom contribute less overall but have a higher proportion of MCP, suggesting that international collaboration is their primary mode of engagement with global issues like water pollution.

Overall, the data suggest that research on industrial water pollution tends to be locally focused in developing countries like China and India. On the other hand, international collaboration is more prevalent in developed nations or countries with limited research capacity. As highlighted by Kohus et al. (2022), international collaboration can amplify research impact by facilitating resource and knowledge exchange. Therefore, countries with SCP-dominated contributions are encouraged to expand their international partnerships, especially for transboundary or global studies. Policies promoting knowledge and technology sharing are also crucial to effectively addressing industrial water pollution at a global scale.

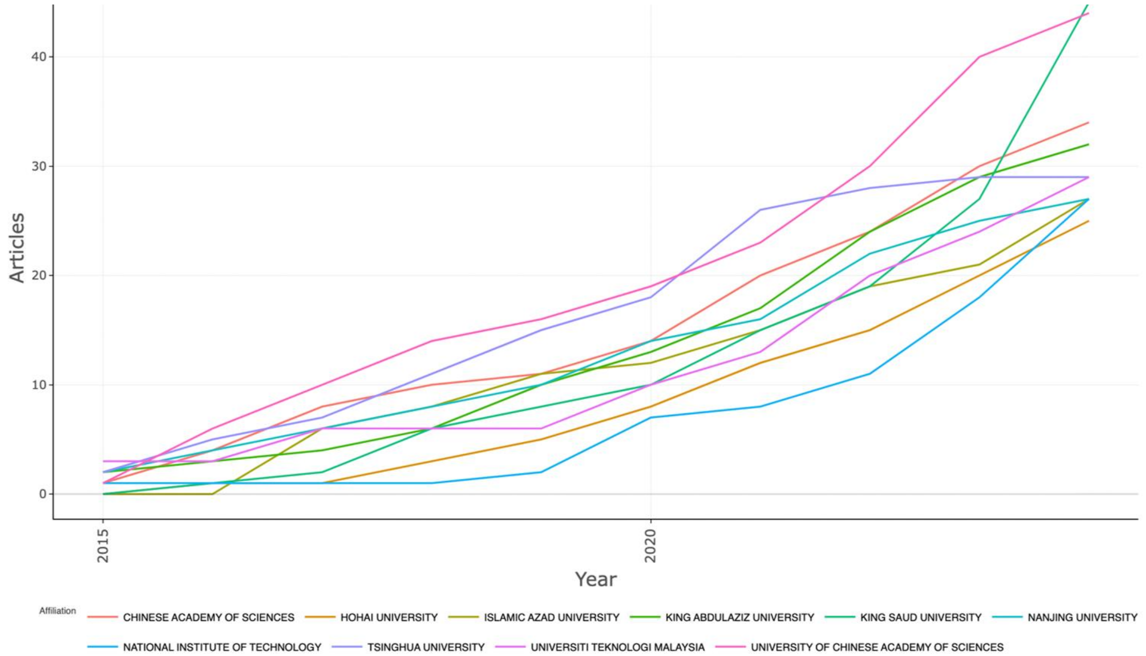

Figure 6. Affiliations' production over time

Based on the data presented in Figure 6, which depicts Affiliations' Production Over Time on the topic of water pollution caused by industrial activities, there is a noticeable trend of increasing publications from various institutions over the period 2015 to 2024. Institutions such as the University of Chinese Academy of Sciences and King Saud University demonstrate significant contributions, with the number of publications steadily rising, reaching nearly 40 by 2024. This trend highlights the growing relevance of research on industrial water pollution and its increasing attention within academic circles, particularly in countries with high levels of industrialization, such as China and India.

Other institutions, including Hohai University, Nanjing University, and Tsinghua University, also exhibit a consistent upward trend in publication output. This growth indicates that East Asia, particularly China, serves as a major contributor to research on industrial water pollution. The increase in publications from these institutions reflects not only the significance of the topic but also the enhanced research capacity in these countries. This development may be supported by government policies prioritizing environmental research, greater funding for relevant studies, and collaboration with global institutions.

3.1.4. Documents: Content and Trends Analysis

Figures 7 and 8 highlight the terms most frequently used in research related to water pollution caused by industrial waste from 2015 to 2024. The dominance of keywords such as "water pollution", "wastewater treatment", "industrial wastewaters", "heavy metals", and "effluents" indicates that the primary focus of research lies in addressing water pollution issues resulting from industrial waste and managing hazardous pollutants like heavy metals. Terms like "adsorption", "bioremediation", and "environmental monitoring" suggest that technical methods, such as adsorption technologies and biologically based approaches, are widely investigated solutions. This aligns with the findings of Liu et al. (2015), who emphasized the importance of technological innovation in wastewater treatment in highly industrialized countries.

Figure 7. Word cloud of publication

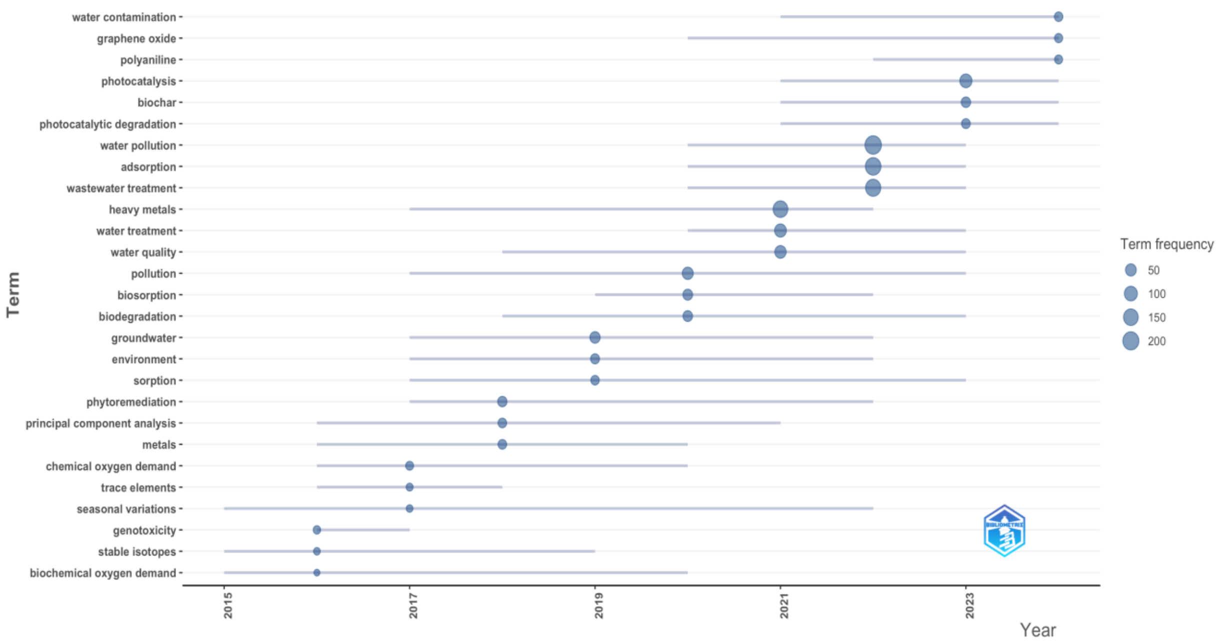

Figure 8. Trend topics of publication

Sustainable approaches like "bioremediation", which utilize microorganisms to eliminate pollutants, have garnered significant attention due to their eco-friendliness compared to conventional methods. Research by El-Sheekh et al. (2016), Yao et al. (2021) and (Sutherland & Ralph, (2019) underscores that bioremediation is an effective strategy, particularly in removing heavy metals that are resistant to natural degradation. Additionally, terms such as "environmental monitoring" and "risk assessment" underscore the importance of monitoring and risk evaluation to ensure the effectiveness of wastewater treatment technologies. Sahu (2024) and Nelson (2023) highlighted that effective environmental monitoring can facilitate early detection of pollution sources, enabling quicker mitigation actions.

These findings reveal a growing emphasis on developing innovative and sustainable technological solutions in research addressing industrial water pollution. To tackle these challenges, several strategic measures are necessary, including advancing wastewater treatment technologies such as adsorption and bioremediation, strengthening environmental regulations, and educating both the public and industry stakeholders about the impact of water pollution. Moreover, international collaboration is crucial to sharing solutions and technologies on a global scale.

In conclusion, research over the past decade reaffirms that a holistic approach—encompassing technology, policy, and public awareness is vital to effectively address water pollution issues. Future research opportunities include developing hybrid technologies for wastewater treatment, exploring environmentally friendly adsorption materials, and integrating digital technologies such as the Internet of Things (IoT) for real-time water quality monitoring. Additionally, risk evaluation of emerging pollutants, such as microplastics and hazardous organic compounds, presents a critical area for further investigation. Future studies could also focus on implementing technologies in diverse environmental conditions, developing predictive models using artificial intelligence (AI) to monitor water pollution, and adopting socio-economic approaches to encourage the industrial sector to embrace environmentally friendly technologies. Combining these approaches is expected to yield effective and sustainable solutions to mitigate industrial water pollution.

The Co-occurrence Networks diagram (Figure 9) further illustrates the relationships between keywords frequently co-occurring in research on water pollution, providing insights into the interconnected themes and research priorities within this domain.

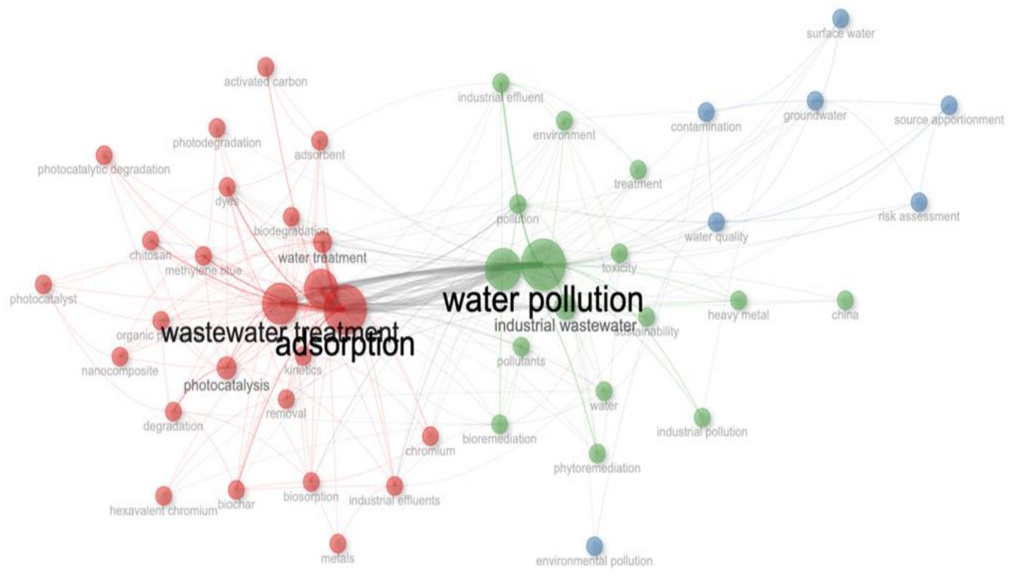

Figure 9. Co-occurrence networks

The Co-occurrence Network analysis on the topic of water pollution caused by industrial waste reveals strong correlations between several key terms such as water pollution, industrial wastewater, wastewater treatment, adsorption, and photocatalysis. These keywords form interconnected clusters, representing the primary research focus during the period of 2015–2024. The Green Cluster focuses on water pollution, encompassing issues like industrial effluent, toxicity, bioremediation, and sustainability. This indicates that much of the research highlights the environmental impact of industrial waste and the mitigation efforts, particularly those using biological approaches such as bioremediation. The Red Cluster emphasizes waste treatment methods, especially through adsorption and photocatalysis. Keywords like activated carbon, nanocomposite, and biochar reflect the growing trend in exploring eco-friendly materials for wastewater treatment technologies. The Blue Cluster focuses more on water quality, involving specific pollutants such as heavy metals, and surface water, and risk-based approaches like risk assessment. This cluster is essential for monitoring the broader impact of water pollution on ecosystems and assessing the risks associated with contamination. This Co-occurrence Network analysis highlights the multidimensional nature of water pollution research, with a strong focus on pollution mitigation technologies, environmental sustainability, and the monitoring of water quality and ecosystem health.

3.2. Systematic Literature Review Results

In the ever-evolving field of research, the growing volume of scientific publications necessitates that researchers focus their analyses on the most relevant and influential works. In the context of water pollution caused by industrial waste, 2,523 articles have been published to date. This study conducts an in-depth analysis of 30 selected articles to ensure a more focused examination of the most impactful scientific works, as determined by the highest average citations per year. Articles with high citation rates reflect their relevance, quality, and significant influence within their respective research fields (van Raan, 2005a). Selecting this number of articles enables a comprehensive exploration without losing representation of key trends.

Cited Total Per Year (CTPY) refers to the total number of citations an article, journal, or publication receives annually. This metric indicates how frequently a study is referenced or cited by others within a given time frame, often serving as a measure of the impact or influence of a scientific work within the academic community. The higher the annual citation count, the greater the likelihood that the article holds significant influence or relevance within its field (Abdullah, 2022). Highly cited articles not only demonstrate that their findings have gained widespread recognition within the scientific community but also tend to reflect innovation and substantial contributions to the advancement of knowledge (Cai et al., 2023; Thelwall and Sud, 2022).

In this study, the analysis focuses on waste types and industrial sources, mitigation methods, and the outcomes achieved in these research efforts. Analyzing these highly cited articles enables researchers to delve deeper into current trends, widely accepted methodologies, and the broader impact of the research on its field (Moed, 2006). Moreover, selecting relevant and impactful articles ensures a more targeted analysis, providing sharper insights into critical issues and the future directions of this research area (Bornmann and Daniel, 2007; Marzi et al., 2024).

As highlighted by van Raan (2005), highly cited articles reflect the quality and impact of research, offering a clear picture of the progression of scientific knowledge within a field. Analyzing these widely referenced studies also allows researchers to identify works that have established new theoretical foundations or driven methodological advancements in subsequent research (Abdullah, 2021; Supriadi et al., 2022). Therefore, articles with the highest citation rates not only signify the relevance and quality of the scientific work but also provide a broader perspective on ongoing research trends. By focusing the analysis on these articles, researchers can gain a clearer understanding of the significant contributions made by these studies, as well as the challenges and progress encountered in this field. This approach strengthens the argument that selecting highly cited articles is an efficient and effective way to conduct a focused analysis within the broad and rapidly evolving landscape of research on water pollution caused by industrial waste.

Table 3. Summary of highly cited research on wastewater treatment

Author and Year	CTPY	Waste type	Method	Result
(Rafiq et al., 2021)	177.25	Textile industry	Semiconductor photocatalysts	Several semiconductor nanocatalysts have been proven to be potential photocatalysts

Author and Year	CTPY	Waste type	Method	Result
				for treating wastewater-containing textile dyes.
(Carolin et al., 2017)	162.5	Industrial waste/ Heavy metals	Coagulation, Membrane filtration, Adsorption, Electrochemical treatment, Electrodialysis, Ion exchange, Photocatalysis, Biological treatment, Oxidation	The coagulation process is effective at removing pollutants, but it generates sludge and secondary pollutants that require further treatment. Ion exchange offers low operational costs and good results, but it is vulnerable to fouling, while flotation results in lower sludge formation compared to coagulation. Membrane separation requires a small space and can kill pathogens, but its efficiency decreases due to backwashing. Chemical precipitation is ineffective for low-concentration heavy metals and generates toxic sludge, while electrochemical treatment is environmentally friendly but limited by the short lifespan of electrodes. Adsorption emerges as a promising alternative for removing heavy metals, although its use is still limited to laboratory-scale applications.
(Rashid et al., 2021)	150.5	Industrial waste/ Dyes, heavy metals, surfactants, personal care products, pesticides, and pharmaceuticals.	Fenton oxidation and electrochemical oxidation, adsorption, and membrane filtration.	Adsorption is a simple, sustainable, cost-effective, and environmentally friendly technique for wastewater treatment compared to other existing technologies.
(Talvitie et al., 2017)	128.88	Wastewater treatment plants (WWTPs)/ microplastic	Disc filters (DF), rapid sand filters (RSF), dissolved air flotation (DAF), and membrane bioreactor (MBR)	Removed > 95% of microplastics (>20 mm) during the treatment.
(Azimi et al., 2017)	123.25	Industrial waste/ Heavy metals	Electrochemical and physicochemical methods, membrane filtration, photocatalytic processes, and nanotechnology treatments	Reverse osmosis (RO), nanofiltration (NF), adsorption, chemical precipitation, electroflotation, and electrocoagulation, can completely remove (>99%) the heavy metals or reduce their dosage to standard limits under optimum conditions. Electrodeposition showed varying removal efficiency for metals from 12 to 92.1 %.
(Islam et al., 2023)	121.5	Textile dyes/ textile industry	Adsorption using activated carbon, bioremediation using microorganisms, and oxidation using hydrogen peroxide.	Bioremediation methods have great potential in addressing textile dye waste in an environmentally friendly manner, but their effectiveness is often lower compared to physical and chemical methods. A combination of technologies is considered the most effective way to sustainably reduce the impact of waste

Author and Year	CTPY	Waste type	Method	Result
(Waliullah et al., 2023)	105	Methyl orange (MO)/ Textile and paper industry	Adsorption. Chitosan-treated nanocomposite	Chitosan-based nanocomposites showed high adsorption performance for MO
(Syafrudin et al., 2021)	97.75	Pesticide waste	Adsorption using activated carbon, bioremediation with microorganisms, photocatalysis, and Advanced Oxidation Processes (AOPs)	AOPs and adsorption are highly effective in removing pesticides, though bioremediation offers a more environmentally friendly approach. Combining methods is often necessary for optimal results.
(Chan et al., 2022)	92	The litter of persistent organic pollutants (POPs)	Biosorption, bioaccumulation and biodegradation	Synergistic interactions between microalgae and bacteria could proficiently enhance the existing biological wastewater treatment system.
(Garcia-Segura et al., 2018)	85.57	Textile dyes, pesticides, and pharmaceutical compounds	Electrochemistry to oxidize and break down pollutants into simpler compounds	Electrooxidation is effective in removing various organic pollutants. However, challenges such as high energy costs, electrode degradation, and efficiency depending on the waste composition remain.
(Anwer et al., 2019)	84.83	Textile dye waste from the textile industry	Photocatalysis, utilizing semiconductor materials to degrade organic pollutants under light	Photocatalysis is effective in breaking down dyes into harmless compounds, but challenges such as low efficiency under visible light and material stability need to be addressed.
(Morin-Crini et al., 2022)	82.67	Persistent organic pollutants, pharmaceuticals, cosmetics, and personal care products	Utilization of wastewater treatment technologies	Wastewater treatment technologies have successfully reduced contaminant concentrations, although their presence is still detected in various water sources worldwide.
(Nasrollahzadeh et al., 2021)	78	Organic and inorganic waste	Nanocatalysts and nanomaterials	Nanocatalysts and environmentally synthesized nanomaterials have significant potential in wastewater treatment and the removal of contaminants from water.
(Dutta et al., 2024)	78	Textile dyes	Bioremediation	Bioremediation is effective in reducing dye concentrations, improving water quality, and reducing health risks associated with textile dye wastewater.
(Uddin et al., 2021)	74	Textile dyes	Adsorption. Using Metal-organic frameworks (MOFs) as adsorbents	MOFs exhibit high adsorption capacity, good stability, and reusability, making them an effective choice for treating dye-contaminated wastewater.
(Theerthagiri et al., 2021)	71	Pewarna Textile dyes, pesticides,	Sonophotocatalytic process, combining sonocatalysis and photocatalysis	Effective in removing pollutants.

Author and Year	CTPY	Waste type	Method	Result
		and heavy metals		
(Lops et al., 2019)	70.5	Textile dyes, specifically Rhodamine B	Sonophotocatalysis uses micro- and nano-ZnO particles to generate free radicals that decompose the dye	Highly effective in removing Rhodamine B from water, with degradation efficiency reaching 100% within 10 minutes, and showing good stability during repeated cycles of use.
(Khan et al., 2021)	70.5	heavy metals and dyes	Adsorption. Magnetic carbon nanotubes (CNT) and CNT-based bucky paper membranes as adsorbents	Magnetic CNTs and buckypaper membranes have high adsorption capacity, good stability, and efficiency in removing heavy metals and dyes from water.
(Ismail et al., 2019)	69.33	Organic dyes	Biocatalytic bioremediation	Effective in removing dyes from water, offering an environmentally friendly and economical alternative.
(Shahid et al., 2020)	66.2	Heavy metals and organic compounds	Bioremediation. Algae cultivation (phytoremediation)	Microalgae are effective in removing pollutants from wastewater and can be used for producing valuable biomass, such as biofuel while contributing to carbon dioxide absorption from the atmosphere.
(Wang and Yang, 2016)	60.56	Industrial wastewater containing heavy metals and toxic chemicals	Not specified	Water pollution is negatively associated with mental and physical health in China.
(Spasiano et al., 2015)	58.8	Cosmetic industry	Photocatalysis based on sunlight, using materials like titanium dioxide (TiO_2) in special reactors to decompose pollutants	Effective in reducing contaminant concentrations, offering an environmentally friendly solution.
(Thakur and Kandasubramanian, 2019)	55.83	Toxic organic compounds and dyes	Adsorption. Graphene-based composites and graphene oxide as adsorbents	These composites have high adsorption capacity and are effective in removing various organic pollutants
(Dharupaneedi et al., 2019)	54	Pharmaceutical, food, and metal processing industries	Membrane-based separation. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and forward osmosis (FO) methods as well as hybrid technologies	Effective in providing clean water with affordable costs and minimal energy requirements.
(Liu et al., 2023)	51.5	Tembaga (Cu^{2+})	Membrane separation, ion exchange, chemical precipitation, electrochemistry, adsorption, and biotechnology.	These methods each have their advantages and disadvantages in the efficiency of removing Cu^{2+}, and the appropriate method selection depends on the specific conditions of the wastewater to be treated.

Author and Year	CTPY	Waste type	Method	Result
(Fu et al., 2020)	51.4	Nitrate ion (NO_3^-), which can originate from industrial and domestic wastewater	Electrochemical nitrate reduction using copper nanosheets to synthesize ammonia	At a low potential (-0.15 V vs RHE), copper nanosheets achieve an ammonia formation rate of 390.1 μg mg^{-1} Cu per hour with a Faradaic efficiency of 99.7%, offering an efficient and clean alternative for ammonia synthesis.
(Gude, 2016)	50.67	Industrial wastewater containing hazardous organic materials	Utilizing microorganisms in Microbial Fuel Cells (MFCs) to oxidize organic materials in wastewater.	MFCs are effective in removing pollutants from wastewater while generating electricity, providing a sustainable solution for wastewater treatment.
(Bhat et al., 2022)	49.67	Heavy metals	Phytoremediation, using hyperaccumulator plants to absorb, stabilize, or detoxify heavy metals from the environment	Phytoremediation is a realistic and promising strategy for removing heavy metals from contaminated areas, using plant species that are tolerant to heavy metals.
(Bouabidi et al., 2019)	49	Organic pollutants	Immobilization of microbial cells, where microorganisms are placed in a supporting matrix to enhance contaminant biodegradation in wastewater	This technique can increase the efficiency of contaminant removal by more than 60%.
(Pereira et al., 2021)	47.75	Organic dyes from textile industries	Adsorption. Composite hydrogels as adsorbents	Composite hydrogels are effective in adsorbing various types of dyes, offering a promising solution for treating wastewater contaminated with dyes.

The analysis of data from various studies provides profound insights into wastewater treatment methods addressing pollution from diverse sources, including textile and pesticide industry effluents and others. Each treatment approach has distinct advantages and limitations that influence its practical application.

Coagulation, one widely adopted method, efficiently removes pollutants by binding harmful particles into flocs. This technique is particularly effective for wastewater containing suspended solids and easily sedimentable compounds. Carolin et al. (2017) highlighted that the sludge generated post-coagulation requires further processing, such as stabilization or thermal treatment, to minimize environmental impact. While coagulation proves effective in the initial treatment stages, advanced sludge management remains critical to mitigate its negative environmental effects. Adsorption is gaining traction with advanced materials such as metal-organic frameworks (MOFs) and chitosan-based nanocomposites. Research by Uddin et al. (2021) and Waliullah et al. (2023) demonstrates the high adsorption capacity of MOFs, which can absorb various pollutants, including heavy metals and organic compounds. MOFs offer customizable properties that enhance their performance, while chitosan-based nanocomposites are more environmentally friendly due to their biodegradability and natural origins. However, Waliullah et al. (2023) emphasized challenges in scaling these materials for industrial applications, citing high production costs and inconsistencies in large-scale production. Despite promising laboratory results, optimizing adsorption materials for industrial and large-scale use remains a significant challenge.

Advanced Oxidation Processes (AOPs), such as photocatalysis and sonophotocatalysis, present solutions for degrading persistent organic pollutants. (Anwer et al. (2019) and Lops et al. (2019) demonstrated that photocatalysis using semiconductors like TiO_2 can break down organic pollutants at the molecular level using ultraviolet energy. While effective for treating harmful compounds like textile dyes, Lops et al. (2019) noted that photocatalysis is energy-intensive, especially under suboptimal conditions such as low light or unstable catalysts. Sonophotocatalysis, which combines ultrasonic waves with photocatalysis, improves efficiency but faces similar energy consumption and visible light effectiveness challenges. Thus, while AOPs hold immense potential, addressing energy costs and scalability issues is essential for broader applications.

In terms of sustainability, biological technologies such as bioremediation and phytoremediation emerge as attractive options due to their ability to utilize living organisms in pollutant reduction. (Islam et al. (2023) and Bhat et al. (2022) demonstrated that bioremediation, using microorganisms to decompose organic pollutants, is environmentally friendly and sustainable. Similarly, phytoremediation, which employs plants to absorb heavy metals from soil and water, effectively reduces contamination levels. However, both methods are often less efficient than chemical and physical alternatives. Syafrudin et al. (2021) and Rashid et al. (2021) suggest hybrid approaches combining bioremediation with chemical or physical methods, such as photocatalysis, to enhance wastewater treatment efficiency. Their studies indicate that integrating biological and technological methods accelerates pollutant degradation, resulting in faster and more effective processes.

Overall, these findings reveal that while each wastewater treatment method offers distinct advantages, key challenges include scalability, energy efficiency, and secondary pollutant management. Future research must focus on hybrid techniques that combine multiple technologies, innovative and efficient materials, and optimizing sustainable technologies. These efforts will enhance wastewater treatment efficiency, reduce environmental impacts, and lower operational costs, enabling widespread adoption in the wastewater treatment industry.

Material innovations play a crucial role in improving the efficiency and sustainability of existing technologies. Significant advancements in this field include the development of nanocatalysts, graphene-based composites, and more stable and efficient visible-light photocatalysts. According to Nasrollahzadeh et al. (2021) and Thakur & Kandasubramanian (2019), these materials offer remarkable advantages, such as increased reaction rates for pollutant removal, particularly in photocatalysis. For instance, nanocatalysts and graphene have large surface areas that enhance adsorption and reactivity toward organic and inorganic pollutants. Their stability under visible light enables optimal performance with lower energy consumption, reducing dependence on external energy sources. However, challenges such as material degradation during prolonged use and high production costs hinder industrial-scale adoption. Thakur & Kandasubramanian (2019)observed that prolonged chemical reactions during usage lead to reduced efficiency, making long-term durability a critical concern for these materials.

In addition to material innovations, sustainability in wastewater treatment technologies is an essential focus. Microbial fuel cells (MFCs), which oxidize organic matter in wastewater to generate electricity, provide a dual solution by treating wastewater while producing energy Gude (2016) highlighted that MFCs convert chemical energy in organic matter into electrical energy for industrial applications, simultaneously reducing water pollution. While promising, MFCs systems require optimization to improve efficiency and reliability at an industrial scale. Gude (2016) emphasized that despite the significant potential of MFCs, challenges in enhancing energy efficiency and minimizing operational costs remain barriers to broader implementation.

This analysis provides deep insights into the challenges and opportunities in wastewater treatment. Existing technologies, such as photocatalysis, bioremediation, and MFCs, have proven effective, but future research must prioritize developing hybrid methods that integrate multiple technologies to enhance efficiency. Innovations in more stable and cost-effective materials, such as nanocatalysts, and advancements in sustainable technologies will enable more efficient, affordable, and environmentally friendly wastewater treatment. These technological developments align with global sustainability goals and ensure the protection of water resources, critical for the well-being and survival of future generations.

4. Conclusions

Based on the Scopus database, the number of publications related to water pollution caused by industrial waste has increased annually, with a total of 2,523 publications from 2015 to 2024, peaking at 423 publications in 2024. The highest number of publications came from China, with 1,908 publications, followed by India with 1,154 publications. The bibliometric analysis reveals a significant growth in research on industrial water pollution over the last decade (2015-2024). Key themes emerging from the studies include the impact of industrial waste on aquatic ecosystems, the effectiveness of water treatment technologies, and the role of regulatory frameworks in addressing pollution. Collaboration between researchers from developed and developing countries has increased, reflecting the importance of global cooperation in tackling this issue. Keywords such as "industrial waste," "heavy metals," "water treatment," and "sustainability" indicate a strong focus on problem identification and solution development. However, the analysis also highlights the lack of interdisciplinary approaches that integrate technological, social, and policy dimensions simultaneously.

In wastewater treatment, technologies such as photocatalysis, bioremediation, and microbial fuel cells (MFCs) have proven effective; however, challenges related to scalability, energy efficiency, and secondary pollutant management remain. Future research must prioritize the development of hybrid methods that combine multiple technologies, as well as innovations in more stable and cost-effective materials, such as nanocatalysts. These advancements will enhance wastewater treatment efficiency and support global sustainability goals, while also safeguarding vital water resources for future generations.

Several gaps in existing research need to be addressed, including a geographical imbalance, with most studies conducted in developed countries and insufficient focus on developing nations facing severe water pollution. Additionally, there is a lack of research linking scientific findings to practical policy measures and evaluating the effectiveness of existing regulations. Therefore, policymakers need to strengthen evidence-based regulations, develop localized solutions, and fund research focused on cost-effective and adaptable water treatment technologies. Public awareness campaigns are also crucial for enhancing the public's understanding of water pollution and the importance of sustainable practices.

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