



Global perspectives on industrial wastewater management: A bibliometric analysis of research output

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ABSTRACT

As the population and urbanization continue to grow, we expect an increase in industrial demand, which will lead to higher water consumption and, consequently, the generation of substantial amounts of industrial wastewater (IWW). This presents significant environmental challenges that necessitate effective treatment solutions. This study addresses the gap in the existing literature by conducting a bibliometric analysis of 1,714 research papers on IWW treatment published in the Scopus database from 2015 to 2024. The findings indicate that over 59.7 % of these publications emerged within the past five years, with a peak of 244 papers published in 2022, reflecting an increased recognition of the necessity for effective IWW treatment approaches. The Journal of Water Process Engineering is identified as the leading journal in this domain. The analysis reveals that the majority of research is concentrated in the fields of chemistry and chemical engineering, with India and China contributing the highest outputs, at 11.79 % and 10.44 %, respectively. The University of Chinese Academy of Sciences is highlighted as a significant contributor, with seven publications and 74 citations, underscoring its prominence in IWW research. The studies indicate a focused interest in addressing various pollutants from industrial wastewater, including chemical oxygen demand (COD), dyes, and heavy metals. Furthermore, this body of research highlights a significant shift from traditional treatment methods toward integrated strategies that combine multiple techniques to enhance efficacy and sustainability in IWW treatment. Electrocoagulation, adsorption, and activated carbon are identified as the predominant treatment methods being explored for specific types of IWW, particularly textile and tannery wastewater. This research significantly contributes to the understanding of contemporary trends and advancements in IWW treatment, emphasizing the critical role of innovative methodologies in effectively addressing pollutant removal and promoting environmental sustainability.

1. Introduction

Water resources and quality are under a lot of strain due to the world's ongoing population expansion and urbanization (Christian et al., 2023; Hamaideh et al., 2024). This issue is not limited to developing countries; even developed nations experience persistent water shortages exacerbated by pollution from industrial activities (Christian et al., 2023; Hamaideh et al., 2024; Amr et al., 2024). Furthermore, the United Nations Sustainable Development Goal 6 (SDG 6) ensuring access

to clean water and sanitation—has grown more important given estimates that more than a billion people may experience water shortages by 2025 (Amdeha, 2023). According to the World Health Organization (WHO), around 1.6 million deaths in 2018 were attributed to water pollution, highlighting the critical need for clean water management (Amdeha, 2023; Naidu et al., 2021; Sanganyado, 2022). Industries such as petroleum refining (Jiad and Abbar, 2024), textile manufacturing (Christian et al., 2023), dairy industry (Faraj et al., 2024), pharmaceuticals (Al-Qodah et al., 2024; Al-Zghoul et al., 2023), paint industry

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(Nair et al., 2021), leather industry (Khilji et al., 2022), and pulp and paper industry (Patel et al., 2021) are among the largest consumers of water, resulting in substantial amounts of wastewater that contain a variety of pollutants. For instance, the textile industry alone is known to generate approximately 20 % of global wastewater (Amdeha, 2023). The industrial capacity for manufacturing increased from 1.2 billion tons in 2000 to 2.3 billion tons in 2017, largely due to the fourth industrial revolution (Amdeha, 2023; Naidu et al., 2021; Sanganyado, 2022). This growth has correspondingly led to a rise in industrial effluents, further contaminating water sources with toxic heavy metals, phenolic compounds, and other persistent pollutants (Badawi et al., 2023; Kamali et al., 2019).

Industrial effluents exhibit a wide range of characteristics that depend on the products manufactured and the chemicals used in the production process (Dvořák et al., 2016; Amr et al., 2023). These effluents often contain high concentrations of organic and inorganic pollutants, dissolved and suspended solids, poisonous compounds, non-biodegradable materials, and different colors, all of which are harmful to human health and the environment (Bilińska et al., 2020; Ayangunna et al., 2016). With industrial activities consuming enormous amounts of fresh water and discharging large volumes of untreated effluent, effective wastewater management strategies are essential to mitigate these impacts and promote sustainable development (Ashrafi et al., 2015; Badawi et al., 2021; An et al., 2023). The intensity of pollution is especially alarming in developing nations, where the production of raw materials generates higher pollution levels compared to finished products (Amr et al., 2023; An et al., 2023; Tong and Elimelech, 2016; Nazari et al., 2023). These nations often lack the necessary treatment technologies, leading to severe environmental degradation and public health crises (An et al., 2023; Tong and Elimelech, 2016; Nazari et al., 2023). However, the treatment of industrial wastewater (IWW) is complex due to the diverse compounds present at varying concentrations (Badawi et al., 2023; Badawi et al., 2021), and each type of wastewater can differ significantly, even within the same industry (Badawi et al., 2021). Currently, researchers are exploring various treatment technologies, such as adsorption (Liu et al., 2021), electro-coagulation (EC) (Al-Zghoul et al., 2023; Amr et al., 2023), membrane filtration (Liu et al., 2021), advanced oxidation processes (AOPs) (Islam et al., 2023), coagulation/flocculation (C/F) (Amr et al., 2024), and membrane bioreactors (Dvořák et al., 2016), focusing on optimizing performance (Liu et al., 2021), understanding treatment dynamics (Liu et al., 2021), and targeting specific pollutants (Islam et al., 2023). Besides, after appropriate treatment, wastewater is regarded as a significant resource for reuse and recycling, providing economic advantages (Amdeha, 2023; Naidu et al., 2021).

The field of IWW treatment faces significant challenges due to a lack of quantitative methods that systematically summarize existing literature. This gap complicates the identification of research hotspots and future trends from a macro perspective. Therefore, emerging new trends and directions that may eventually aid in the creation of useful and the development of economical and practical applications in the future (Baarimah et al., 2024; Shokri and Fard, 2023). Bibliometrics emerges as a vital tool evaluations of scientific activity that are both quantitative and qualitative (Zheng et al., 2015; Wallin, 2005; Purba et al., 2024). Bibliometrics employs mathematical and statistical techniques to examine the exterior characteristics of literature, including books, papers, and patents, as well as their references, which include citations and co-citations (Purba et al., 2024; Mao et al., 2021; Fard et al., 2023). This analysis reveals quantitative patterns within specific subject areas, allowing for the evaluation of research productivity across individuals, institutions, and countries (Mao et al., 2021; Fard et al., 2023). The knowledge gathered from bibliometric analysis helps researchers discover new study directions in addition to improving our comprehension of the state of the field (Mao et al., 2021; De Battisti and Salini, 2013).

Moreover, bibliometric analysis is essential for forecasting future

advancements within specialized fields (Mao et al., 2021; Durán-Sánchez et al., 2020). Co-citation analysis, which examines citation relationships among documents, further enriches this approach by enabling researchers to identify and analyze quantitative relationships within their areas of interest (De Battisti and Salini, 2013). Such analyses yield valuable bibliometric data that provide an overview of research efforts, helping to uncover new research fronts (Zheng et al., 2017). Ultimately, bibliometrics can be divided into two primary categories: one focusing on research activity levels, which highlights significant subjects, nations, and journals, and the other that uses social network analysis and relationship indicators to explore interconnections among keywords, countries, and institutions (De Battisti and Salini, 2013; Ramos-Rodríguez and Ruíz-Navarro, 2004). These categories collectively elucidate central and peripheral themes in a field and illustrate how they evolve over time (De Battisti and Salini, 2013). As a result, bibliometric analysis aids researchers in better comprehending the state of knowledge, identifying important publications, and evaluating trends in a given scientific subject, all of which point to areas that require more investigation. These analyses provide details on the main ideas and dynamic procedures of a certain field of research (Vasseghian et al., 2023; Jamrah et al., 2024).

Despite valuable bibliometric studies conducted on IWW treatment, limitations exist. Some researchers have restricted their focus to specific regions or topics, such as EC (Huang et al., 2024), adsorption (da Silva Santos et al., 2021), C/F (Noor and Ngadi, 2024), membrane bioreactor (Segredo-Morales et al., 2023), textile wastewater (Halepoto et al., 2022), tannery wastewater (Li et al., 2022; Zhao et al., 2022), dairy wastewater (Faraj et al., 2024; Praful and Pattnaik, 2023), and pharmaceutical wastewater treatment (Al-Qodah et al., 2024; Wang et al., 2023). Our research aims to perform a temporal bibliometric analysis of the publications on IWW within this framework, specifically covering the period from 2015-2024. This study is novel in its comprehensive approach, quantitatively examining characteristics such as the most active authors and countries, the top journals by publication output, the number of publications, affiliations, subject areas, co-authorship networks among countries, and the identification of emerging thematic areas and research gaps in the field. The papers analyzed were exclusively sourced from the Scopus database, ensuring a robust and systematic evaluation of IWW treatment literature. By focusing on recent publications, this study aims to supplement and expand upon the findings described in earlier research, providing a clearer picture of the current trends and advancements in IWW treatment.

2. Materials and methods

2.1. Data source and search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was used in this study to review the literature (Durán-Sánchez et al., 2020). Regarding the sort of meta-analysis, we did not incorporate meta-analysis procedures into the analysis, but rather adhered to PRISMA recommendations. One of the useful methods for building a sizable and reproducible database in systematic literature reviews is bibliometric analysis (Durán-Sánchez et al., 2020). When doing bibliometric analysis, it is important to clearly define the study's goals and provide thorough explanations of how the relevant materials were found. One may argue that bibliometric analysis's widespread acceptability and success can be attributed to its capacity to provide a comprehensive overview of the research industry, outputs, organizations, and trends (Biberici, 2023; Donthu et al., 2021; Firdaus et al., 2019). In order to comprehend the relationship between journal citations and provide a perspective on the current or emerging field of research, they may be utilized extensively for the evaluation and analysis of vast amounts of scholarly data (Firdaus et al., 2019). According to academics, bibliometric analysis and its consequences might support future study and development (Zheng et al., 2017). Bibliometric

approaches are used in many different fields because of these features (Hallinger and Suriyankietkaew, 2018; Müßigmann et al., 2020). This study used bibliometric analysis to monitor the trends and advancements of IWW treatment research. The Scopus database for the years 2015–2024 was used to analyze publications. Because the Scopus database covers many academic disciplines and has a wealth of published articles in the literature sector, it was chosen (Vasseghian et al., 2023; Donthu et al., 2021). A literature search was conducted using the following query string and the provided keywords: “(TITLE-ABS-KEY (“Treatment*”) AND (“Industrial” OR “Industry”) AND (“Wastewaters” OR “Effluent*”) OR “Sewage”) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (SRCTYPE, “j”)) AND (LIMIT-TO (LANGUAGE, “English”))). Fig. 1 below provides an illustration of the search approach.

According to the keywords, our initial search produced 2672 publications in the form of books, book chapters, conference papers, review articles, and articles, as shown in Fig. 1. We then went ahead and narrowed down this corpus to just include journal articles written in English. Following this screening procedure, 1714 publications were chosen.

2.2. Data extraction and filtering

Data was extracted, organized in the Scopus database, and then

converted into Comma-Separated Values (CSV) files. To guarantee the authenticity and dependability of the data, a number of filtering techniques were used during the source selection process. Procedures including eliminating redundancies and implementing inclusion and exclusion criteria according to language, document type, and source were put into place throughout these stages. Following the segmentation and search of the information, the source name, authors, and affiliations were carefully examined annually. The quality of the discovered papers was also taken into account in the document title, abstracts, and keywords sections. Regretfully, the data filterization procedure required that any inaccurate or incomplete entries be appropriately removed in order to bring the data.

2.3. Data analysis

The practice of creating, drawing, and presenting bibliometric maps for readability is common in bibliometric research. This method appears to make working with literature and identifying the connections between certain sources easier (Durán-Sánchez et al., 2020). We downloaded the data for VOSviewer software processing as we needed to see the results and familiarize ourselves with the bibliometric results’ outlines. The open-source, user-friendly VOSviewer software is used for networking and bibliometric data visualization (Durán-Sánchez et al., 2020). There are certain aspects in which it is different from other

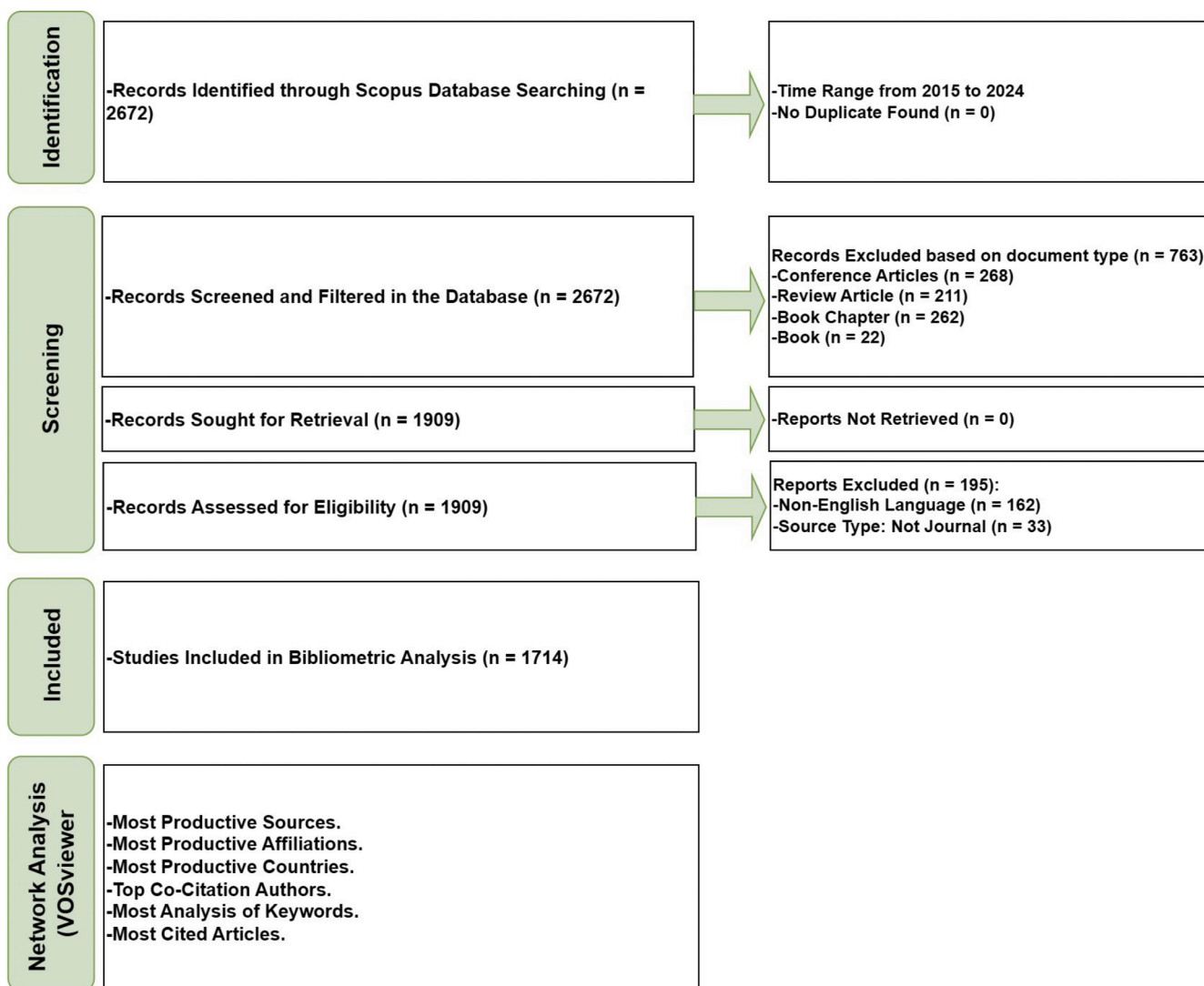


Fig. 1. Research methodology.

software programs, such as CiteSpace, SciMAT, Gephi, and Bib Excel (Vasseghian et al., 2023; Zahoor et al., 2022). VOSviewer software was used for data processing and analysis since it has text-mining skills and can handle networks of very large sizes (Hallinger and Suriyankietkaew, 2018). VOSviewer software was used to create bibliometric maps, which show the relationships between the chosen articles and aid in the discovery of relationships, trends, and patterns in the literature (Kasavan et al., 2021). One of the program's advantages is its ability to dynamically alter the labels being used, which fits the algorithm's goal of displaying co-occurrences (Kasavan et al., 2021).

The investigation focused on four main areas: the article database, the author keywords used in the papers and journals where the articles were published, and the countries of origin. For bibliometric studies, these elements are crucial because they provide a thorough picture of the state of the research (Van Eck and Waltman, 2013; Usmani et al., 2021; Rai et al., 2020). Publications, average normalized citations, and total link strength (TLS) were all considered while determining the analysis's parameters. These metrics are helpful in assessing the effect and visibility of the item (Rai et al., 2020).

Only journal articles were among the 1714 papers that were found throughout the search. 356 distinct publication sources or venues provided these materials. The literature on the topic was authored by 4481 writers from 2635 different institutions throughout the globe. Significant contributions to the literature were made by authors from 99 different nations. A total of 12679 citations demonstrated the cumulative impact of these 1714 publications, highlighting their significance in the academic community. The study of author-supplied keywords revealed a complex tapestry of 3122 distinct phrases, providing more insight into the research emphasis of the literature. The main bibliometric conclusions drawn from the review of the literature on IWW treatment are briefly summarized in Table 1.

3. Results and discussion

3.1. Trend of annual publications

Fig. 2a shows how the number of published papers on IWW and the six major Scopus subject categories has changed over time. A total of 1,714 research papers in this area published between 2015 and July 2024 were found through a search of the Scopus database. Of them, "articles," which include 1714 articles and 64.1 % of all publications, is the most prevalent form. "Book chapters" (9.8 %), "review articles" (7.9 %), "conference articles" (10 %), and others (like "book" and "not journal") comprise the others. The other categories were not further taken into consideration because "articles" made up the majority of publications.

The annual publication trends, illustrated in Fig. 2b, reflect the dynamic nature of research activity in IWW treatment methodologies over the past decade. Starting with 112 published papers in 2015, there was a steady increase to 138 in 2016. Subsequent years exhibited fluctuations, with 119 publications in 2017, 154 in 2018, and a notable rise to 167 in 2019. The upward trend continued, peaking at 208 publications in 2021 and reaching 244 articles in 2022. However, a slight decline was observed in 2023, with 231 papers published. As of 2024, 153 articles have already been published, indicating the potential for further

contributions before the year concludes. This data not only highlights a generally positive trend in research activity but also emphasizes the growing importance and focus on IWW treatment methodologies. By situating these findings within the context of identified research gaps, we can better understand how they contribute to advancing knowledge in this field. It is essential to distinguish these contributions from existing literature, as they reflect emerging themes and innovative approaches that warrant further exploration.

The distribution of publications on IWW treatment reveals significant patterns in research production across various scientific fields, highlighting areas of both strength and opportunity. Notably, "chemical engineering" emerges as the dominant field, accounting for 66.69 % of the published studies. This prominence underscores the critical role that chemical engineers play in developing and optimizing treatment processes, designing efficient systems, and ensuring compliance with environmental regulations.

In addition, the field of "chemistry" contributes 22.29 % of the research, emphasizing the vital importance of understanding chemical reactions and properties in IWW treatment. Insights into the chemical composition of wastewater and the interactions during treatment processes are essential for formulating effective purification strategies, thereby addressing gaps in current methodologies. Furthermore, the "energy" domain, representing 11.03 % of the publications, highlights the intersection between IWW treatment and energy resource management. This area focuses on the energy consumption associated with various treatment methods and the potential for energy recovery from effluent, emphasizing the necessity for sustainable practices in IWW management. Overall, these findings illustrate the interdisciplinary nature of IWW treatment research and its connection to broader environmental challenges.

3.2. Preeminent journals for research on the IWW treatment

The analysis of the top sources publishing research on IWW treatment highlights significant insights into the field's landscape. The top 15 sources that have published a lot of material about the IWW treatment are included in Table 2, together with information about their publication counts, total citations, TLS, h-index, and SCImago Journal Rank (SJR). The majority of the papers on IWW treatment are found in a few high-profile scholarly journals. According to the statistics, there is a noticeable concentration of research output in high-impact journals, indicating that these sources are essential for expanding our understanding of this area.

Notably, the "Journal of Water Process Engineering" leads with 49 publications and 800 citations, demonstrating a strong influence within the field, with an average of 16.33 citations per paper. In contrast, the "Desalination of Water Treatment" journal has 45 publications but only 125 citations, resulting in an average of approximately 2.75 citations per article, indicating a more specialized impact despite its significant output. The "Journal of Environmental Chemical Engineering" stands out with 37 publications and an impressive 1,551 citations, yielding an average of 41.89 citations per publication, which reflects its widespread recognition and influence in the research community. Other notable journals, such as "Chemosphere" and "Environmental Science and Pollution Research," have published 32 and 28 articles, respectively, with citation counts of 1,263 and 401. This suggests that these journals not only contribute a substantial volume of research but also provide valuable knowledge that resonates within the scientific community.

Furthermore, journals like "Science of the Total Environment" and "Separation and Purification Technology" have made their mark with 21 and 20 publications and citation averages of 17.57 and 20.9, respectively. The "Journal of Environmental Management" and "Journal of Cleaner Production" also contribute significantly, with 19 publications and 234 citations, and 18 publications and 474 citations, respectively. Lastly, "Water Science and Technology" has 17 publications with 148 citations, indicating a steady, albeit less influential, contribution to the

Table 1
Key bibliometric findings summarized.

Description	Findings
Countries	99
Authors' Affiliations	2635
Publication Venues	356
Author Keywords	3122
Authors	4481
Total Citations	12679
Publications	1714

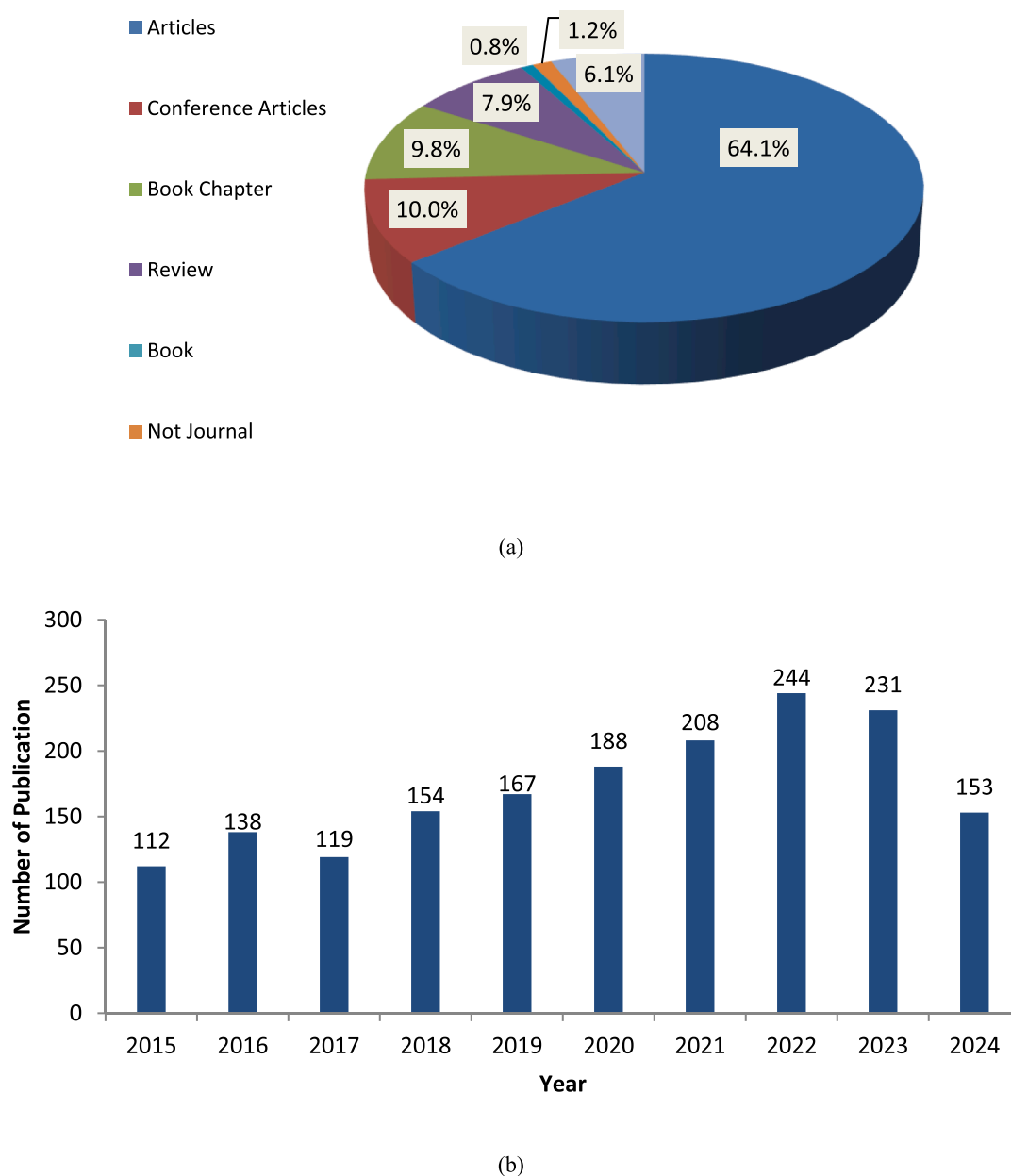


Fig. 2. (a) The percentage of document type reports for research on IWW treatment; (b) The annual of IWW treatment research-related publication every year, as determined by the Scopus database until September 2024 (n = 1714).

field. Overall, this analysis underscores the diverse contributions and varying impacts of these journals in advancing research on IWW treatment methodologies.

Journals with 12 papers published in this field of study between 2015 and 2024 were identified as the primary sources. Fifteen of the sources that were found satisfied these requirements, as shown in Fig. 3. These 15 periodicals serve as the primary information sources for IWW treatment research and are essential to the development of the subject.

Overall, this analysis illustrates a robust network of high-impact journals dedicated to IWW treatment, emphasizing the importance of these platforms in disseminating pivotal research findings. The varying citation counts reflect both the influence and the specific focus areas of each journal, suggesting that researchers should consider these factors when selecting publication venues for their work.

3.3. Country IWW treatment collaboration network

The current bibliometric study provides a comprehensive overview of the leading nations contributing to research on IWW treatment. As detailed in Table 3, key data such as publication counts and associated citation metrics highlight the significant roles of various countries. China and India emerge as frontrunners in this field, with 202 and 179 published papers, respectively, and citation totals of 3,598 and 3,248. This substantial output positions both countries as major players in IWW treatment research, reflecting their robust research infrastructure and active scholarly engagement.

Following closely are Iran and Turkey, which contributed 65 and 62 publications, respectively, garnering total citations of 637 and 568. These figures indicate a growing interest and investment in wastewater treatment research within these nations. Brazil, Egypt, and Saudi Arabia

Table 2
The top 15 sources by citation count for IWW treatment study.

Source	TLS	Documents	Citations	H-index	SJR
Journal of Water Process Engineering	630	49	800	89	1.278
Desalination and Water Treatment	574	45	125	83	0.256
Journal of Environmental Chemical Engineering	550	37	1551	127	1.355
Chemosphere	541	32	1263	311	1.806
Environmental Science and Pollution Research	411	28	401	179	1.006
Science of the Total Environment	278	21	396	353	1.998
Separation and Purification Technology	294	20	418	202	1.533
Journal of Environmental Management	317	19	234	243	1.771
Journal of Cleaner Production	213	18	474	309	2.058
Water Science and Technology	157	17	148	157	0.554
International Journal of Environmental Science and Technology	29	16	95	101	0.598
Chemical Engineering Journal	187	15	359	309	2.852
Water (Switzerland)	106	13	86	102	0.724
Environmental Research	171	12	134	179	1.679
Sustainability (Switzerland)	126	12	147	169	0.672

also demonstrate notable contributions, with 57, 52, and 45 publications, respectively. Brazil’s citation count of 1,298 highlights its strong impact relative to its publication output, while Egypt and Saudi Arabia have accumulated 693 and 643 citations, respectively. This trend underscores the diverse research capabilities across different regions and suggests that these countries are increasingly addressing the challenges associated with IWW management.

Additionally, Malaysia’s 36 publications, along with 303 citations, reflect the relevance of its research output in this area. Other countries,

including Spain, Pakistan, South Korea, and the United States, contribute 33, 30, 29, and 29 publications, respectively, with citation counts of 459, 407, 785, and 512. This indicates a competitive landscape where multiple nations are making valuable research contributions, albeit with varying levels of impact.

Finally, the United Kingdom, Morocco, and Mexico, with 26, 25, and 23 publications, have accumulated 896, 289, and 260 citations, respectively. The disparities in citation counts among these nations suggest differing levels of academic influence and recognition within the global research community. Overall, this analysis highlights the dynamic and diverse contributions of nations to the field of IWW treatment research.

Because of this approach’s great treatment efficiency, IWW treatment has become a global research priority (Costa et al., 2021). A bibliometric examination of the published literature is necessary to have a thorough grasp of the state of research in this area at the moment.

One common paradigm in this field is research cooperation, which is described as the cooperative generation of scientific knowledge (Han

Table 3
Leading 15 countries in terms of IWW treatment publications between 2015 and 2024.

Nation	TLS	Publications	Citations
India	47	202	3598
China	55	179	3248
Iran	14	65	637
Turkey	8	62	568
Brazil	6	57	1298
Egypt	26	52	693
Saudi Arabia	53	45	643
Malaysia	20	36	303
Spain	10	33	459
Pakistan	27	30	407
South Korea	29	29	785
United States	23	29	512
United Kingdom	23	26	896
Morocco	0	25	289
Mexico	5	23	260

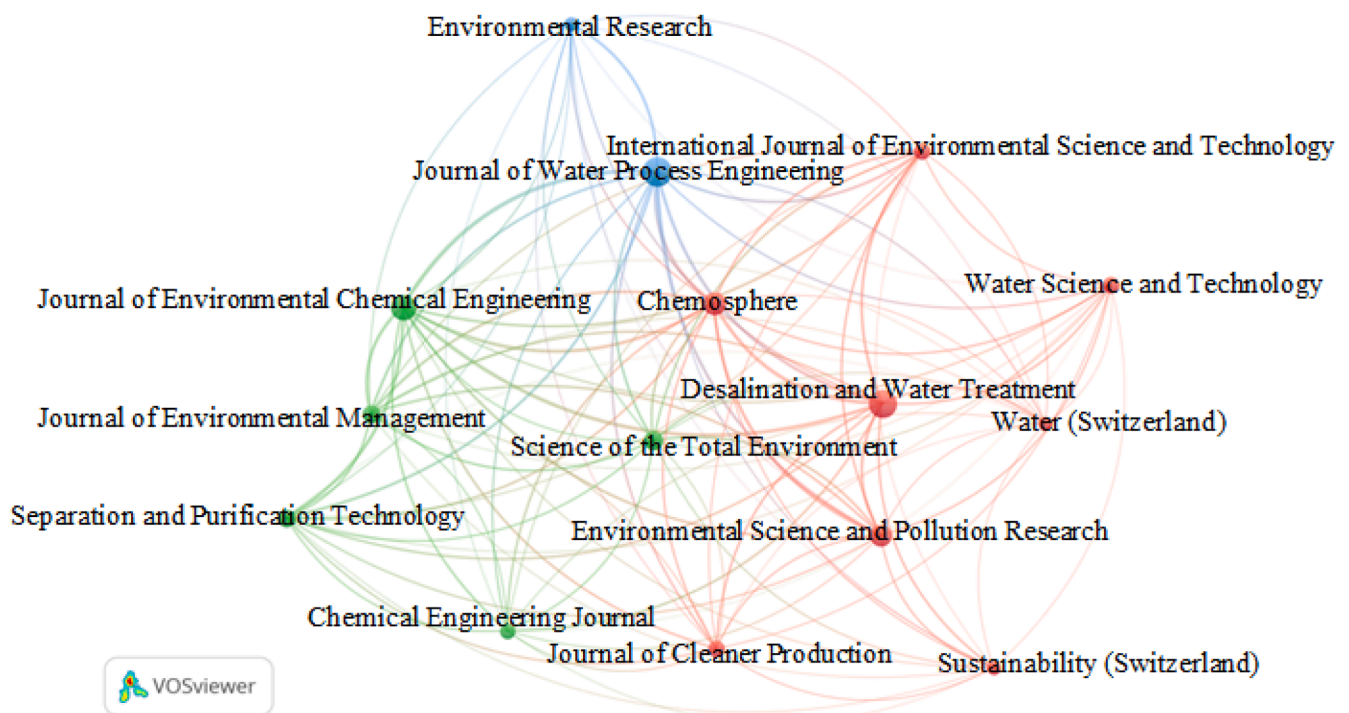


Fig. 3. Co-occurrence map of journals with over 12 articles treating IWW published between 2015 and 2024.

et al., 2014). Collaborations can take place between nations, institutions, and individual writers, among other levels (Han et al., 2014). Using VOSviewer software, a network diagram was created to analyze the network of global partnerships. The participating nations are depicted as labeled nodes in this image, and the lines connecting the nodes indicate the relative contributions of each country to the total project. The thickness of the lines indicates the intensity of the collaborative relationships, and the size of the nodes indicates the number of citations that the articles from each country have received (Van Eck and Waltman, 2010).

As shown in Fig. 4, the network analysis showed that 15 nations have shown a strong interest in studying IWW treatment. The nations with the most significant roles—shown by the thicker connecting linkages and higher node sizes—are probably leading the way in this area of study. The worldwide scope of study endeavors and the key figures propelling the development of IWW treatment procedures might be represented by this data.

All things considered, this analysis shows how research efforts in IWW treatment are distributed globally and emphasizes the disparities in the level of influence that various nations have had in this new field of study. The data indicates that while India and China lead the field, other nations are making significant contributions, reflecting a collaborative international effort to address the pressing challenges of wastewater management. This growing body of knowledge presents opportunities for future research collaborations and policy development aimed at enhancing IWW treatment technologies worldwide.

To identify the leading institutions engaged in research on IWW treatment, a comprehensive map was developed based on 1,714 publications available in the Scopus database, as illustrated in Fig. 5.

Instead than naming particular universities or research organizations, the initial data mostly gave affiliations in terms of departments or colleges. In order to appropriately represent the universities or research institutes involved, this data had to be rearranged, as shown in Table 4.

Among the top affiliations, the “University of Chinese Academy of Sciences,” stands out with seven publications and 74 citations, indicating a strong research presence in the field. Following closely is the “Department of Chemical Engineering at Adama,” which has produced five publications with 49 citations, reflecting significant contributions to the area. The “Department of Applied Chemistry at Razi University in Kermanshah,” has four publications and 22 citations, suggesting that while its output is moderate, it has added valuable insights to the discipline. Notably, the “School of Environmental Science and Engineering at Tianjin University,” also with four publications, boasts an impressive 273 citations, highlighting the high regard and influence of its research.

Other institutions, such as the “Environmental Science and Technology Research Center” and the “Department of Environmental Science at the University of Gujrat,” each with four publications, show varying citation counts of 25 and 15, respectively. This indicates differing levels of impact, with the former suggesting relevance in specific areas of IWW treatment. The “Academy of Scientific and Innovative Research” has also published four articles, achieving 68 citations, which underscores the significance of its research output. Conversely, the “Center of Excellence in Environmental Studies at King Abdulaziz University” and the “Department of Environmental Engineering at Karabuk University,” both with four publications, report lower citation counts of 12. This may suggest that their research is still developing in terms of visibility and influence.

Overall, the analysis reveals a diverse landscape of research in IWW treatment, with varying levels of publication output and citation impact. The “University of Chinese Academy of Sciences” leads in both quantity and quality, while “Tianjin University” stands out for its high citation rates, providing valuable insights for future study collaborations and funding decisions in the area.

These institutions align with the countries that demonstrate significant contributions, reflecting the strong connection between geographical origin and affiliations in this research field. This pattern can be attributed to the countries’ support for scientific research and innovation in IWW treatment, as well as the presence of collaborative networks among institutions within each country.

3.4. Network of co-citation authors in IWW treatment research

One well-known bibliometric method that makes it possible to map the body of existing literature in a systematic manner is co-citation author network analysis (Hallinger and Suriyankietkaew, 2018). The underlying conceptual frameworks and thematic links within a study subject are revealed by this technique, which makes it easier to identify studies that are commonly referenced together. We used the VOSviewer software to do a thorough co-citation network analysis for this investigation. We were able to get important information on the groupings and connections between the articles in the area of interest thanks to our analytical method. The findings of this in-depth analysis are shown in Table 5, which provide a comprehensive picture of the article’s current status in this field. As indicated by their numerous publication outputs, the writers found using this co-citation network analysis have proven to be exceptionally committed and knowledgeable in furthering the academic work in this field. This material is intended to draw attention to the significant personalities and foundational works that have influenced the theoretical underpinnings and scholarly conversation

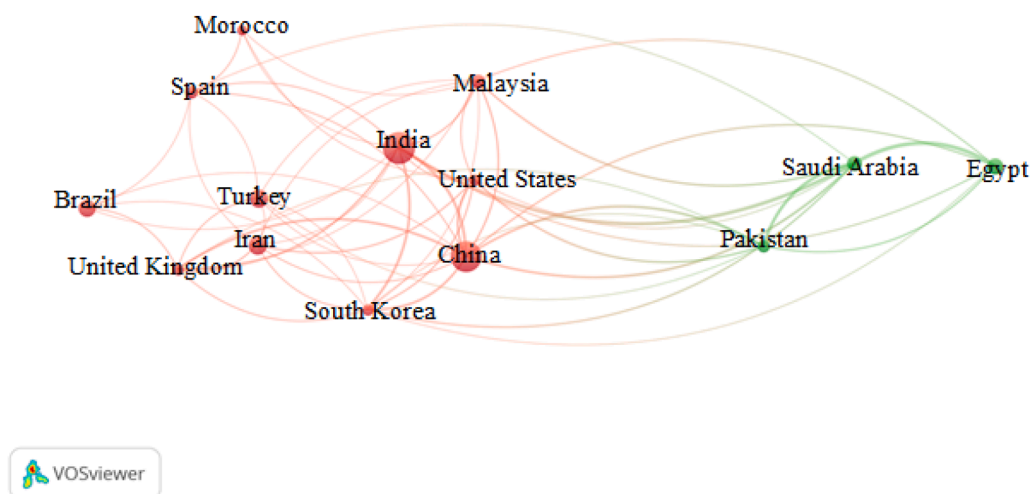


Fig. 4. A network visualization showing the main countries participating in the study on IWW treatment.



Fig. 5. A network visualization showing the main universities involved in the study examining the treatment of IWW.

Table 4

Top 9 universities according to authors' affiliation.

Affiliation	Country	TLS	Documents	Citations
University of Chinese Academy of Sciences	Beijing, China	3	7	74
Department of Chemical Engineering, School of Mechanical, Chemical, and Materials Engineering	Adama	5	5	49
Department of Applied Chemistry, Faculty of Chemistry, Razi University, Kermanshah,	Iran	11	4	22
School of Environmental Science and Engineering, Tianjin University	Tianjin, China	7	4	273
Environmental Science and Technology Research Center, Department of Environmental Health Engineering	Iran	6	4	25
Department of Environmental Science, University of Gujrat, Hafiz Hayat Campus	Gujrat, Pakis	4	4	15
Academy of Scientific and Innovative Research	Ghaziabad, India	2	4	68
Center of Excellence in Environmental Studies, King Abdulaziz University	Jeddah, Saudi Arabia	2	4	12
Department of Environmental Engineering, Faculty of Engineering, Karabuk University	Karabuk	2	4	12

surrounding the subject of the study.

The 1714 articles in the dataset under investigation reflect the work of 4481 distinct authors. It's interesting to see that certain authors have written for many journals, indicating a particular interest in this area. Table 5 displays the relevant information for the most well-known writers together with the number of publications and citations their work has received. It is essential to recognize that while this approach

Table 5

Co-occurrence map of researcher cooperation from 2015 to 2024.

Author	Publications	Author	Citation
Dobrosz-Gómez I.	7	Zheng W.	131
Gómez-García M.Á.	7	Akansha J.	128
Asaithambi P.	7	Iloms, E.	126
Yesuf M.B.	7	Nidheesh, P. V.	114
Gogate P.R.	7	Aadil, M.	97
Alemayehu E.	6	Cai, Q.Q.	88
Govindarajan R.	6	Azari, A.	83
Lucas M.S.	6	Vélez-Pérez, L.S.	78
Peres J.A.	6	Yang, Y.	72
da Silva Jorge N.	5	EL-Mekkawi, D.M.	71
Banu J.R.	5	Kumari, U.	68
Pugazhendi A.	5	Manni, A.	68
Agrawal R.S.	5	He, R.	67
Haan T.Y.	5	Gholipour, A.	66

highlights prolific authors, it may inadvertently exacerbate the Matthew Effect, whereby well-known authors receive more recognition and citations, further enhancing their visibility in the academic community. In our analysis, we identified the 14 most referenced authors in IWW treatment research, as well as 14 key contributors who have published at least five articles in this domain.

Leading the list are Dobrosz-Gómez I., Gómez-García M.Á., Asaithambi P., Yesuf M.B., and Gogate P.R., each with seven publications, demonstrating a substantial research output. Interestingly, these authors were not among the most highly cited in the reviewed literature. Following closely are Alemayehu E., Govindarajan R., Lucas M.S., and Peres J.A., each with six publications, underscoring their significant contributions to the academic discourse surrounding IWW treatment. Additionally, authors such as da Silva Jorge N., Banu J.R., Pugazhendi A., Agrawal R.S., and Haan T.Y., each with four published works, represent a cohort of researchers who have consistently advanced our understanding of the challenges and optimization strategies in wastewater treatment applications.

The author with the highest citation count is Zheng W., with a total of 131 citations. Akansha J. follows closely with 128 citations, while Iloms,

E. (126 citations), Nidheesh, P. V. (114 citations), and Aadil, M. (97 citations) round out the top cited authors. These findings suggest that while the field of IWW treatment embraces a collaborative, multi-author approach, certain researchers have emerged as particularly influential, significantly impacting both publication outputs and citation counts.

3.5. The most cited publications in IWW treatment

The scientific mapping of citation analysis is a crucial method for identifying the intellectual relationships between publications, particularly when one study is referenced in another (Donthu et al., 2021). This approach facilitates the analysis of citation trends and patterns and aids in identifying the most significant research publications within a certain academic area (Bang et al., 2023). In order to do this, the study used citation analysis to look at the published publications. Table 6 displays the top 15 publications with the highest number of citations based on the Scopus database. Adherence to the Scopus database is the sole criterion utilized to rate these articles. This citation analysis offers insightful information about the most significant and important works in the field of IWW treatment research.

The following information summarizes the top seven papers with more than 83 citations that were found using a search of the Scopus database: "Electrocatalytic Nitrate Reduction to Ammonia Using a Self-Activated Ni Cathode: From Basics to Scale-Up for Industrial Wastewater Treatment." The most cited publication, with 131 citations. In 2021, Zheng et al. published this work in the journal *Environmental Science & Technology* (Zheng et al., 2021). This study demonstrates the effectiveness of an *in situ* activated pristine nickel (Ni) electrode for nitrate reduction to ammonia in both laboratory and pilot-scale settings. The self-activated Ni cathode exhibited remarkable activity, selectivity, and stability, achieving ammonium nitrogen (NH_4^+-N) conversion yields of

95.3 % and 97.8 % at nitrate concentrations of 200 mg/L and 2000 mg/L, respectively. According to research, $\text{Ni}(\text{OH})_2$ nanoparticles are formed on the electrode surface during self-activation and are essential for the nitrate reduction reaction (NO_3RR) because they minimize hydrogen evolution events and promote an atomic hydrogen-mediated route. With its high yields and Faradaic efficiency, the self-activated $\text{Ni}(\text{OH})_2/\text{Ni}$ cathode may be readily scaled up to process large amounts of IWW and effectively convert nitrate into ammonia. This research presents an innovative and efficient method for treating nitrate-laden IWW, producing ammonia as a valuable byproduct, thus advancing wastewater management and resource recovery (Zheng et al., 2021).

The research with 128 citations is the second most cited on the list. The article published in *Chemosphere* in 2020 with the title "Treatment of dairy industry wastewater by combined aerated electrocoagulation and phytoremediation process" was written by Akansha et al. (2020). This study examined the efficacy of treating wastewater from the dairy sector using aerated EC in conjunction with phytoremediation. The impacts of several factors, such as electrode type, pH, and voltage, were studied using iron and aluminum electrodes. The results indicated that EC was most effective at neutral pH, with efficiency increasing as voltage was raised. With an initial pH of 7 and a voltage of 5 V, the Al-Fe electrode combination produced a maximum chemical oxygen demand (COD) removal efficiency of 86.4 % after 120 min. When comparing EC-treated wastewater to raw wastewater, a significant increase in *Canna indica* was seen. A 97 % clearance rate of COD was achieved when EC and phytoremediation were combined. Tests for bacterial toxicity also showed that wastewater, whether treated or not, encouraged the development of bacteria. These results highlight how well the combined treatment approach manages effluent from the dairy industry.

The third most referenced paper, authored by Iloms, E., is titled

Table 6
The top 15 most-cited articles.

First Author	Year	Title	Source	Citations	Refs.
Zheng, W.	2021	Self-Activated Ni Cathode for Electrocatalytic Nitrate Reduction to Ammonia: From Fundamentals to Scale-Up for Treatment of Industrial Wastewater	Environmental Science and Technology	131	(Zheng et al., 2021)
Akansha, J.	2020	Treatment of dairy industry wastewater by combined aerated electrocoagulation and phytoremediation process	Chemosphere	128	(Akansha et al., 2020)
Iloms, E.	2020	Investigating industrial effluent impact on municipal wastewater treatment plant in vaal, South Africa	International journal of environmental research and public health	126	(Iloms et al., 2020)
Nidheesh, P. V.	2020	Treatment of mixed industrial wastewater by electrocoagulation and indirect electrochemical oxidation	Chemosphere	114	(Nidheesh et al., 2020)
Aadil, M.	2021	Fabrication of MnO_2 nanowires and their nanohybrid with flat conductive matrix for the treatment of industrial effluents	FlatChem	97	(Aadil et al., 2021)
Cai, Q.Q.	2020	Potential of combined advanced oxidation – Biological process for cost-effective organic matters removal in reverse osmosis concentrate produced from industrial wastewater reclamation: Screening of AOP pre-treatment technologies.	Chemical Engineering Journal	88	(Cai et al., 2020)
Azari, A.	2023	Magnetic multi-walled carbon nanotubes-loaded alginate for treatment of industrial dye manufacturing effluent: adsorption modelling and process optimisation by central composite face-central design.	International Journal of Environmental Analytical Chemistry	83	(Azari et al., 2023)
Vélez-Pérez, L.S.	2020	Industrial acid mine drainage and municipal wastewater co-treatment by dual-chamber microbial fuel cells.	International Journal of Hydrogen Energy	78	(Vélez-Pérez et al., 2020)
Yang, Y.	2020	Activated sludge microbial community and treatment performance of wastewater treatment plants in industrial and municipal zones.	International Journal of Environmental Research and Public Health	72	(Yang et al., 2020)
EL-Mekki, D. M.	2020	Solar photocatalytic treatment of industrial wastewater utilizing recycled polymeric disposals as TiO_2 supports.	Journal of cleaner production	71	(EL-Mekki et al., 2020)
Kumari, U.	2020	Facile method to synthesize efficient adsorbent from alumina by nitric acid activation: Batch scale defluoridation, kinetics, isotherm studies and implementation on industrial wastewater treatment.	Journal of hazardous materials	68	(Kumari et al., 2020)
Manni, A.	2020	New low-cost ceramic microfiltration membrane made from natural magnesite for industrial wastewater treatment.	Journal of Environmental Chemical Engineering	68	(Manni et al., 2020)
He, R.	2023	Tunable Bi-bridge S-scheme $\text{Bi}_2\text{S}_3/\text{BiOBr}$ heterojunction with oxygen vacancy and SPR effect for efficient photocatalytic reduction of $\text{Cr}(\text{VI})$ and industrial.	Separation and Purification Technology	67	(He et al., 2023)
Gholipour, A.	2020	A novel pilot and full-scale constructed wetland study for glass industry wastewater treatment.	Chemosphere	66	(Gholipour et al., 2020)
Venugopal, V.	2021	Seafood industry effluents: Environmental hazards, treatment and resource recovery.	Journal of Environmental Chemical Engineering,	64	(Venugopal and Sasidharan, 2021)

“Investigating Industrial Effluent Impact on Municipal Wastewater Treatment Plant in Vaal, South Africa,” published in the “International Journal of Environmental Research and Public Health,” with 126 citations (Iloms et al., 2020). This study evaluated the effects of industrial wastewater containing hazardous heavy metals on the water quality of the Vaal River, focusing on the Leeuwkuil wastewater treatment plant (WWTP) from January to September 2017. The researchers monitored river samples, WWTP inflow and effluent, as well as physicochemical parameters and heavy metal concentrations from five industrial sources. The results revealed significant differences in pH, total dissolved solids (TDS), dissolved oxygen (DO), COD, biological oxygen demand (BOD), and electrical conductivity (EC), with industrial samples exhibiting higher values. Elevated amounts of aluminum, copper, lead, and zinc were found in industrial effluents using inductively coupled plasma optical emission spectrometry (ICP-OES), with seasonal variations seen for zinc and aluminum. Although the WWTP adhered to most South African Green Drop Standards, the concentrations of copper, zinc, and lead in the treated effluent exceeded permissible limits, posing risks to river health and biodiversity. The study concluded that the WWTP’s capacity was inadequate for effectively reducing heavy metal concentrations due to the high levels of non-biodegradable content in the influent. Recommendations included improving the pre-treatment of industrial effluents, continuous water quality monitoring, and maintaining WWTP infrastructure to mitigate pollution in the Vaal River. Further research on heavy metals in sediments was also suggested to assess ecological risks (Iloms et al., 2020).

In 2020, Nidheesh et al. published a noteworthy study in “Chemosphere” titled “Treatment of Mixed Industrial Wastewater by Electrocoagulation and Indirect Electrochemical Oxidation,” which has been cited 114 times (Nidheesh et al., 2020). This research addresses the challenges associated with treating mixed IWW, emphasizing the effectiveness of electrochemical techniques, specifically EC and indirect electrochemical oxidation. The authors investigated the removal efficiencies for color and COD under various conditions. Their findings revealed that both treatment methods performed optimally at neutral pH levels. Notably, the study compared two connection configurations: monopolar (MP) and bipolar (BP). The results indicated that the MP configuration outperformed the BP setup, achieving a COD removal of 55 % and a color removal of 56 % at a voltage of 1.5 V over one hour, while the BP configuration yielded lower efficiencies of 43 % COD and 48 % color removal. Furthermore, when employing indirect electrochemical oxidation with graphite electrodes at a pH of 7.7 and a voltage of 4 V, the researchers found that the addition of sodium chloride significantly enhanced the removal efficiencies, achieving 55 % COD and an impressive 99.8 % color removal. The study concluded that the indirect electrochemical oxidation process, combined with EC using aluminum electrodes, presents promising and cost-effective options for treating mixed IWW (Nidheesh et al., 2020).

Another important study, conducted by Aadil et al. and published in “FlatChem,” focuses on the fabrication of manganese dioxide (MnO_2) nanowires and their hybridization with MXene to treat IWW (Aadil et al., 2021). This research has garnered 97 citations and emphasizes the development of a stable MXene nanohybrid to overcome performance limitations associated with MXene’s tendency to restack and oxidize. The study employed various characterization techniques to confirm the structural integrity and properties of the nanohybrid. The photocatalytic and antibacterial activities of the nanohybrid were assessed using *Staphylococcus aureus* bacteria and crystal violet dye under solar light conditions. Remarkably, the H_2O_2 -supported MXene/ MnO_2 nanohybrid exhibited superior photocatalytic activity, achieving approximately 91.5 % dye degradation after 50 min with a rate constant of 0.045 min^{-1} , demonstrating its effectiveness compared to pure MnO_2 and the MXene/ MnO_2 hybrid. According to the results, the MXene/ MnO_2 nanohybrid is a powerful photocatalyst that may break down dangerous organic dyes and stop microorganisms from growing in industrial waste. Successful synthesis and integration were verified through SEM, PXRD,

and FTIR analyses, highlighting the potential of this nanohybrid for environmental remediation (Aadil et al., 2021).

In the Chemical Engineering Journal, the study “Potential of combined advanced oxidation–Biological process for cost-effective organic matter removal in reverse osmosis concentrate produced from industrial wastewater reclamation: Screening of AOP pre-treatment technologies,” written by Cai et al. (2020), has received 88 citations. The viability of using AOPs in conjunction with biological treatment to eliminate organic pollutants from genuine reverse osmosis concentrate (ROC) is assessed in this study. UV/ H_2O_2 , UV/Persulfate (PS), Fenton, and Fluidized Bed Reactor (FBR)-Fenton processes were the four AOPs evaluated. The most economical pre-treatment choice was the FBR-Fenton method, which had a chemical cost of $\$0.519/\text{m}^3$. The FBR-Fenton procedure achieved a COD removal efficiency between 30.9 % and 59.8 % by considerably increasing the BOD_5/COD ratios in ROC by 4.2 to 10 times under ideal circumstances (10 mM H_2O_2 , 1.25 mM Fe^{2+} , pH 3, and a hydraulic retention duration of 1 h). The FBR-Fenton technique was combined with a biological activated carbon (BAC) column that had a 120-minute empty bed contact period to improve treatment. This integrated system continuously eliminated organics from ROC during a 120-day period, yielding in an effluent COD level of 26 mg/L and an average COD removal efficiency of 69 %. According to analysis, the FBR-Fenton procedure successfully eliminated 83 % of the humic compounds that were the predominant organic species in ROC while simultaneously enhancing biodegradability. Finding the best AOP for ROC pre-treatment, combining certain AOPs with BAC for continuous flow therapy, and examining how AOPs affect BAC performance were the objectives of the study. Planctomycetes was the predominant phylum under high salinity circumstances, according to microbiological characterization of the BAC media. The FBR-Fenton procedure encouraged its growth, which improved the removal efficiency of COD.

Lastly, Azari et al. published a study in the “International Journal of Environmental Analytical Chemistry” that focuses on the use of magnetic multi-walled carbon nanotubes loaded with alginate for treating industrial dye manufacturing effluent (Azari et al., 2023). This research, which has received 83 citations. In this work, magnetic multi-walled carbon nanotubes loaded with alginate (CNT-Alg- Fe_3O_4) are used to evaluate the removal of dyes from raw textile effluent. The goal is to use response surface methodology-based central composite face-centered design (RSM-CCF) to optimize important parameters including pH, adsorbent dose, and contact duration. Energy-dispersive X-ray spectroscopy (EDS), scanning electron microscopy (SEM), vibrating-sample magnetometer (VSM), FTIR spectroscopy, and X-ray diffraction (XRD) were among the methods used to characterize the adsorbents. A high match between the model and the experimental data was shown by the results, which showed a low p-value (7.9714e-13), a relative standard deviation (RSD) of 1.121, and a coefficient of determination larger than 0.953. The removal effectiveness achieved 98.43 % with an adsorption capacity of 138.97 ADMI/g under ideal circumstances, which included a pH of 3, an adsorbent dosage of 10 g/L, and a contact period of around 85.55 min. The adsorption process is monolayer and chemical in character, as shown by data fitting with the Langmuir isotherm ($R^2 = 1$, $X^2 = 0.012$) and pseudo-second-order kinetics ($R^2 = 0.993$, $X^2 = 0.015$). The dye removal process was spontaneous and endothermic, according to thermodynamic characteristics ($\Delta H^\circ > 0$, $\Delta S^\circ > 0$, and $\Delta G^\circ < 0$). Ten successive studies using the same adsorbent revealed a decline in removal effectiveness of around 11.94 %. This study demonstrates how well CNT-Alg- Fe_3O_4 treats wastewater from textiles, which is a significant component of IWW, particularly in the dyeing and finishing processes.

As shown in Table 5, these highly referenced published papers emphasize the use of various treatment techniques for various forms of IWW, such as dairy wastewater (Akansha et al., 2020), municipal wastewater (Vélez-Pérez et al., 2020; Yang et al., 2020), food sector effluents (Shrivastava et al., 2022), and textile wastewater (Azari et al., 2023; Aghilesh et al., 2021). This body of research highlights a

significant shift from traditional treatment methods—primarily biological, physical, and chemical approaches—toward integrated treatment strategies that combine multiple techniques to enhance efficacy and sustainability to treat IWW (Akansha et al., 2020; Nidheesh et al., 2020; Cai et al., 2020; He et al., 2023).

In order to increase treatment efficiency, the majority of the research included in Table 5 concentrated on integrated procedures that involve pre- or post-treatment of wastewater (Akansha et al., 2020; Nidheesh et al., 2020; Cai et al., 2020; He et al., 2023). For instance, Akansha et al. (2020) investigated the synergistic effects of combining phytoremediation with aerated EC for dairy wastewater treatment. Their findings illustrate how integrated approaches can leverage the strengths of different methodologies to achieve higher removal rates of contaminants, thus addressing the specific challenges posed by diverse wastewater compositions. Moreover, the research emphasizes the critical need to address a range of contaminants, including heavy metals (Zheng et al., 2021; Iloms et al., 2020), organic compounds (Akansha et al., 2020; Iloms et al., 2020; Nidheesh et al., 2020), and dyes (Aadil et al., 2021).

Techniques such as EC (Akansha et al., 2020) and electrocatalytic reduction (Zheng et al., 2021) have shown promise in effectively removing these pollutants. For example, studies focused on electrochemical methods demonstrated significant improvements in contaminant removal efficiency when optimized parameters such as pH and voltage were applied. The use of AOPs has also been highlighted as a viable strategy, particularly in enhancing the biodegradability of wastewater, which facilitates subsequent biological treatment stages (Cai et al., 2020). Nanomaterials have emerged as an innovative solution for adsorption techniques, demonstrating their potential to enhance the removal of complex organic dyes from textile wastewater (Azari et al., 2023). Research into magnetic multi-walled carbon nanotubes loaded with alginate indicates high adsorption capacities and efficiencies, reinforcing the importance of utilizing advanced materials in wastewater treatment applications (Zheng et al., 2021; Venugopal and Sasidharan, 2021).

The overarching objectives of these studies align with the pressing need to enhance resource recovery and reduce the environmental impact of IWW. By focusing on integrated and innovative treatment approaches, the research contributes to developing more sustainable wastewater management practices. This approach not only addresses immediate treatment challenges but also aligns with broader environmental goals, such as minimizing pollution and maximizing the recovery of valuable resources from wastewater streams (Zheng et al., 2021; Venugopal and Sasidharan, 2021). In conclusion, the analyzed studies reflect a significant advancement in the field of IWW treatment, demonstrating the effectiveness of integrated methodologies and innovative materials. As the research continues to evolve, the findings will play a crucial role in shaping future wastewater treatment technologies and policies, ultimately leading to improved environmental outcomes and resource sustainability.

3.6. The IWW treatment's main research topics

According to Biberici (2023), co-occurrence analysis can be useful in determining research subjects and evaluating the dynamics of research fronts within a certain field of study. Using VOSviewer to apply the Scopus data we had collected to our research, we established a minimum keyword count of seven. Therefore, 60 strings were retrieved via this stage out of 3122 author keywords.

A list of terms that reached or beyond the study's predetermined threshold is shown in Table 7. It should be noted that the authors' keywords, not the index keywords, were the main focus of this investigation. The top 60 keywords are shown in Table 7 in descending order based on their TLS. The ranking of these keywords was determined using a rigorous scientific research that took into consideration factors including cumulative link strength, the number of links pointing to each keyword, and the frequency of their occurrence.

Table 7

Top 60 keywords from the research published on IWW treatment.

Keywords	Cluster	TLS	Occurrence
Wastewater Treatment	1	105	119
Wastewater	1	67	68
Industrial Wastewater	8	58	80
Electrocoagulation	3	55	49
Adsorption	6	53	56
Treatment	1	31	19
Heavy Metals	1	29	25
Response Surface Methodology	2	25	18
Optimization	3	22	23
Textile Wastewater	3	21	20
Activated Carbon	3	20	15
COD	2	20	21
Ceramic Membrane	4	19	14
Ozonation	5	19	12
Ultrafiltration	4	19	12
Nanofiltration	4	18	11
COD	1	17	20
Membrane Bioreactor	1	17	11
Microfiltration	4	17	10
Coagulation	3	16	16
COD Removal	8	16	17
Industrial Wastewater Treatment	7	16	29
Textile Effluent	5	15	11
Artificial Neural Network	2	12	7
Cost Analysis	5	12	7
Electro-Fenton	3	12	11
Kinetics	7	12	11
Membrane Fouling	4	12	13
Natural Coagulant	1	12	7
Advanced Oxidation	7	11	17
Coagulation-Flocculation	1	11	12
Constructed Wetlands	1	11	8
Dye Removal	4	11	8
Microbial Community	2	11	8
Photo-Fenton	5	11	9
Biodegradability	3	10	7
Photocatalysis	6	10	15
Toxicity	3	10	8
Circular Economy	1	9	9
Fenton	3	9	11
Industrial Effluent	6	9	14
Oxidation	7	9	7
Sustainability	1	9	11
Industrial Wastewater Treatment Plant	2	9	13
Industrial Wastewater Treatment	4	8	7
Effluent Treatment	6	8	7
Industrial Effluents	1	8	8
Microalgae	2	8	9
Phytoremediation	1	8	9
Resource Recovery	5	8	9
Bacteria	2	7	7
Anaerobic Digestion	6	6	8
Biological Treatment	1	6	11
LCA	5	6	8
Persulfate	7	6	8
Tannery Wastewater	1	6	7
Zero Liquid Discharge	5	6	7
Activated Sludge	2	5	8
Chemical Oxygen Demand	6	5	7
Microbial Fuel Cell	8	5	10

According to the findings of the keyword overlap study, “wastewater treatment,” “wastewater,” and “industrial wastewater” are the phrases most often used in the field of IWW treatment research. “Wastewater treatment,” “wastewater,” “industrial wastewater,” “electrocoagulation,” “adsorption,” “treatment,” “heavy metals,” “response surface methodology,” “optimization,” and “textile wastewater” were among the top 10 keywords associated with IWW treatment. The TLS values showed that “wastewater treatment” (105), “wastewater” (67), “industrial wastewater” (58), “electrocoagulation” (55), and “adsorption” (53), were the highest values. The relative significance of these fundamental ideas in the realm of IWW treatment is demonstrated by

these findings.

The top 60 keywords in the Scopus database are displayed in Table 7. The following potential and related fields are reflected in the keywords employed in the field of IWW treatment: First, “textile wastewater,” “textile effluent,” “industrial effluent,” “textile wastewater,” and “tannery wastewater” all refer to the primary source of contaminated water produced by different industrial operations. These wastewaters contain contaminants that can be harmful to the environment, yet they are treatable (Chen et al., 2020; Deng et al., 2021; Kuleyin et al., 2021; Alazaiza et al., 2023; Alazaiza et al., 2024). These terms are interconnected, as each one represents a specific type of polluted water arising from particular industries. For instance, “textile wastewater” and “tannery wastewater” are specific cases of “industrial wastewater” that require specialized treatment to remove chemical and biological pollutants.

Secondly, “wastewater treatment,” “heavy metals,” “COD,” “dye removal,” “toxicity,” and “biodegradability” refer to the main goals of treating polluted water. In wastewater treatment, the goal is to remove harmful substances, including heavy metals and dyes, while reducing COD to minimize toxicity levels. Effective treatment methods focus on removing these pollutants to enhance the biodegradability of the effluent. Ultimately, the aim is to ensure that the treated water is safe for release back into the environment, minimizing its effect on ecosystems and human health. Thirdly, the terms “electrocoagulation,” “coagulation,” “electro-fenton,” “natural coagulant,” “advanced oxidation processes,” “coagulation/flocculation,” “photo-fenton,” “photocatalysis,” “fenton,” and “oxidation” refer to the chemical processes employed in treating IWW. These processes are designed to remove pollutants through various chemical reactions, improving water quality and facilitating further treatment.

Fourthly, the terms “adsorption,” “activated carbon,” “ceramic membrane,” “ozonation,” “ultrafiltration,” “nanofiltration,” “microfiltration,” “membrane fouling,” and “persulfate” describe the physical processes used in wastewater treatment. These methods focus on the physical removal of contaminants, utilizing techniques like filtration and adsorption to achieve effective treatment outcomes. Fifthly, the terms “membrane bioreactor,” “constructed wetlands,” “microbial community,” “microalgae,” “phytoremediation,” “bacteria,” “anaerobic digestion,” “biological treatment,” “activated sludge,” and “microbial fuel cell” refer to the biological processes utilized for treating IWW. These processes harness the natural metabolic activities of microorganisms to break down organic matter, enhancing the degradation of pollutants and promoting sustainable treatment solutions.

Sixthly, the terms “Response surface methodology,” “optimization,” “artificial neural network,” and “kinetics” are phrases that refer to methods for improving IWW treatment procedures. A statistical technique called response surface methodology (RSM) is used to plan studies and assess how different factors affect treatment results (Faraj et al., 2024). Optimization focuses on adjusting these variables to maximize pollutant removal and process efficiency. Artificial neural networks (ANNs) utilize complex data patterns to predict treatment effectiveness, while kinetics studies the rates of chemical reactions involved in wastewater treatment (Al-Qodah et al., 2024; Baarimah et al., 2024; Alazaiza et al., 2022; Fard et al., 2023). When combined, these methods aid in the creation of more successful and efficient treatment plans.

Finally, the terms “cost analysis,” “circular economy,” “sustainability,” “resource recovery,” “life cycle assessment,” and “zero liquid discharge” encompass key concepts for evaluating and enhancing IWW treatment. Cost analysis identifies cost-effective solutions, while the circular economy promotes resource reuse and waste minimization. Sustainability focuses on practices that meet current needs without compromising future resources. Resource recovery extracts valuable materials from wastewater, and life cycle assessment evaluates the environmental impacts throughout the treatment process. Zero liquid discharge (ZLD) aims to eliminate wastewater discharge entirely, advocating for complete water reuse and a more sustainable approach to

IWW management.

The network diagram that follows, which is shown in Fig. 6, reveals the keyword co-occurrences in the context of the research papers pertaining to the IWW treatment.

The nodes in Fig. 6’s schematic stand in for the elements, and their positions and shapes demonstrate how likely it is that the elements will co-occur. By examining the term co-occurrence network map, eight distinct clusters of different colors can be identified, each of which represents a distinct topic within the subject matter under study. Each of the latter’s clusters, shown by the various colored nodes in the picture, looks at a distinct discipline in the IWW treatment. The thickness of the connections between the entities indicates the strength of a connection, while the size of the nodes in the diagram indicates the frequency of occurrence.

The network map utilized in this investigation displays eight sizable groupings, as seen in Fig. 6. Stated differently, the first cluster in the network map of this study, shown by the red highlight, stands for “sustainability in IWW treatment: techniques and approaches for environmental and public health.” Green-colored terms in the second cluster emphasize “innovative approaches in the optimization of IWW treatment processes.” The blue-colored third term cluster stands for “advanced techniques for the treatment of textile wastewater.” The color yellow, which represents the fourth cluster of terms, offers “membrane techniques for efficient dye removal in IWW treatment.” Purple, which stands for the fifth cluster of terms, is associated with “sustainable approaches to textile effluent treatment and resource recovery.” Light blue is used to symbolize the sixth cluster of keywords, which is about “synthetic approaches in adsorption and photocatalysis for effective industrial effluent treatment.” Orange stands for the seventh cluster of terms, which is about “kinetic studies and AOPs in IWW treatment.” The color brown, which stands for the ninth cluster of terms, was associated with “enhancing COD removal in IWW through microbial fuel cell technology.”

The first cluster of these sets focuses on wastewater treatment procedures that are necessary for public health and environmental protection because they eliminate pollutants from water impacted by human activity. It encompasses wastewater from residential, commercial, and industrial sources, often containing harmful pollutants that require effective treatment. Processes include biological, chemical, and physical approaches to reduce pollutants, with heavy metals like lead and mercury necessitating specialized treatment. COD serves as a key measure of organic pollution, while membrane bioreactors enhance treatment efficiency through biological processes and membrane filtration. Natural coagulants assist in particle removal, and constructed wetlands provide cost-effective treatment solutions. The circular economy concept promotes sustainability through waste reduction and resource reuse. Phytoremediation utilizes plants to clean pollutants, and biological treatment effectively degrades organic matter. Tannery wastewater, rich in pollutants, requires specialized treatment to minimize environmental harm.

In the second cluster, the focus is on enhancing IWW treatment processes through various interconnected methodologies. RSM is a statistical technique utilized to optimize different parameters within treatment systems. By analyzing experimental data, RSM helps identify the most effective conditions for improving treatment performance. Building on the insights gained from RSM, ANNs are employed to model complex relationships between variables. These computational models can analyze large datasets, predict outcomes, and optimize treatment conditions, thereby improving the overall efficiency of wastewater treatment methods. A critical component of these methodologies is the microbial community, which comprises microorganisms such as microalgae and bacteria. These organisms play a vital role in degrading pollutants within effluent. Their interactions are particularly important in biological treatment processes, such as activated sludge systems, where they work together to effectively break down organic matter and contaminants. Collectively, these elements—RSM, ANNs, and microbial

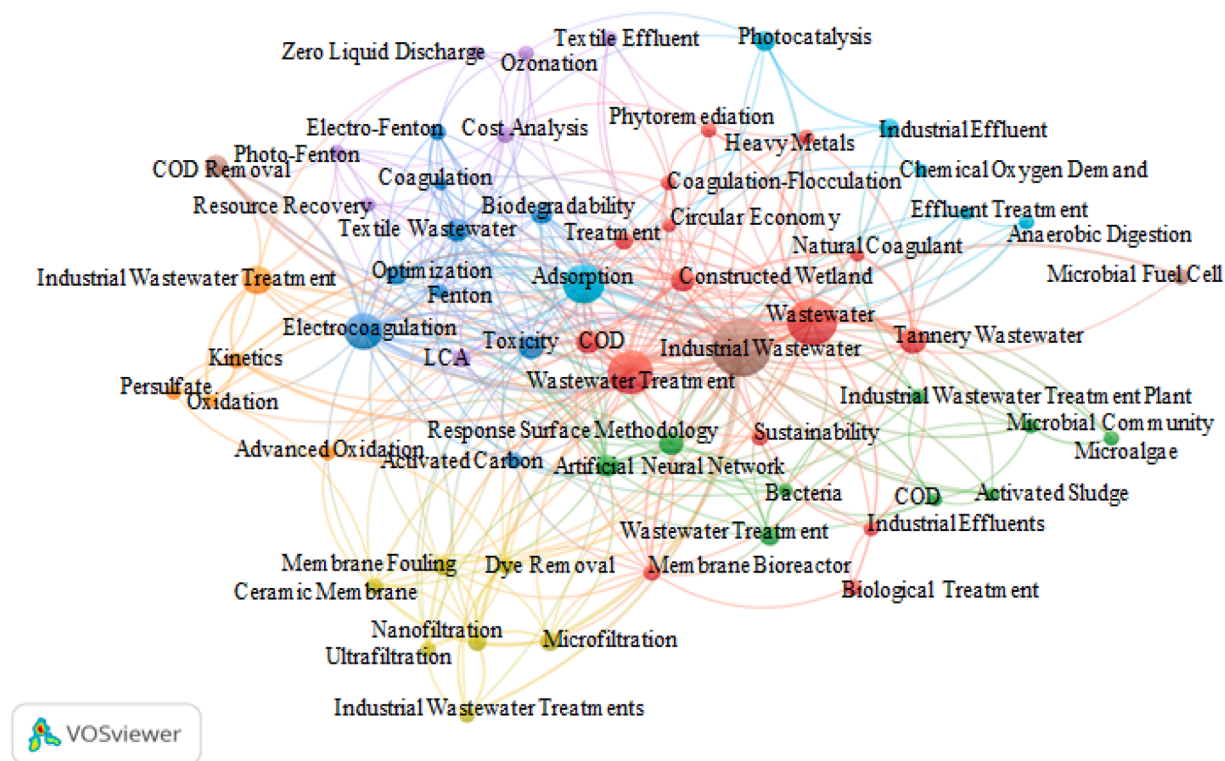


Fig. 6. Author keyword co-occurrence grouping in a network visualization.

communities—create a robust framework for enhancing the sustainability and efficiency of IWW treatment, addressing both environmental and operational challenges.

The third cluster focuses on innovative techniques for treating textile wastewater, which is often characterized by high levels of pollutants and toxicity. EC is a process that utilizes electrical currents to destabilize and remove suspended particles and contaminants from wastewater, offering a highly effective treatment option. The optimization of this process is crucial to enhance its efficiency and reduce operational costs. In conjunction with EC, activated carbon can be employed to adsorb remaining contaminants, further improving water quality. Coagulation is a fundamental method where chemicals are added to promote the aggregation of particles, which can then be removed from the water. The Electro-Fenton method combines EC with Fenton's reagent, utilizing iron and hydrogen peroxide to generate hydroxyl radicals that effectively degrade organic pollutants. The focus on biodegradability and toxicity is essential in wastewater treatment, as these factors determine the safety and environmental impact of the treated effluent. Fenton's process, similar to Electro-Fenton, also employs the generation of hydroxyl radicals to enhance the degradation of recalcitrant compounds. Together, these keywords represent a comprehensive approach to improving the treatment of textile wastewater, addressing both efficiency and environmental concerns.

The fourth cluster emphasizes the role of membrane methods in the treatment of IWW, particularly for dye removal. Ceramic membranes are increasingly used due to their durability and resistance to fouling, making them suitable for harsh wastewater conditions. Ultrafiltration (UF), nanofiltration (NF), and microfiltration (MF) are key processes that utilize membranes with varying pore sizes to separate contaminants from water. MF targets larger particles and suspended solids, while UF is effective for smaller organic molecules and colloids. NF can remove even smaller dissolved substances, including certain dyes and salts, providing a comprehensive approach to treating complex wastewater streams. A significant challenge in using these membrane technologies is membrane fouling, which occurs when contaminants accumulate on the

membrane surface, reducing its efficiency and lifespan. Addressing fouling is crucial for maintaining optimal performance in dye removal processes. Together, these keywords illustrate the advancements and challenges in employing membrane technologies for effective IWW treatment, particularly in the textile industry.

The fifth cluster highlights sustainable strategies for managing textile effluent, focusing on both treatment and resource recovery. Ozonation is a powerful oxidation process used to degrade organic pollutants and dyes in wastewater, enhancing the overall treatment efficiency. Coupled with this, the Photo-Fenton process utilizes light to activate Fenton's reagent, generating hydroxyl radicals that effectively break down complex contaminants. Conducting a cost analysis is essential for evaluating the economic feasibility of these advanced treatment technologies, ensuring that the benefits outweigh the expenses. Additionally, life cycle assessment provides a comprehensive evaluation of the environmental effects associated with the entire method, from treatment to disposal. The concept of ZLD aims to eliminate wastewater discharge by recovering and reusing all water and resources, thus minimizing environmental impact. Together, these keywords represent a holistic approach to textile effluent management, emphasizing the importance of sustainability and resource efficiency in IWW treatment.

The sixth cluster focuses on advanced methods for treating industrial effluent, emphasizing the importance of combining various treatment technologies. Adsorption is a widely used method for eliminating pollutants from wastewater, where pollutants adhere to the surface of adsorbents, effectively reducing their concentration. Photocatalysis is another innovative approach that utilizes light-activated catalysts to degrade organic pollutants, offering a sustainable method for treating effluents. This process can be particularly effective for breaking down complex compounds that are resistant to conventional treatments. In the context of effluent treatment, monitoring COD is crucial, as it indicates the amount of organic matter present and helps assess treatment efficiency. Additionally, anaerobic digestion is an effective biological treatment method that breaks down organic materials in the absence of

oxygen, producing biogas that can be harnessed for energy. Together, these keywords illustrate a multifaceted approach to industrial effluent treatment, integrating adsorption, photocatalysis, and anaerobic digestion to enhance pollutant removal and promote sustainability.

The seventh cluster explores the interplay between kinetics and AOPs in the treatment of IWW. IWW treatment often involves complex chemical reactions aimed at removing contaminants effectively. Understanding the kinetics of these reactions is essential for optimizing treatment conditions and improving efficiency. AOPs utilize powerful oxidants to degrade organic pollutants that are typically resistant to conventional treatments. One such oxidant is persulfate, which, when activated, generates sulfate radicals capable of breaking down a wide range of pollutants. The oxidation reactions facilitated by AOPs are crucial in achieving significant reductions in pollutant concentrations, leading to cleaner effluents. Together, these keywords highlight the importance of studying reaction kinetics and employing AOPs to enhance the effectiveness of IWW treatment.

Finally, the eighth cluster focuses on innovative approaches for addressing the challenges of IWW treatment, particularly in the context of COD removal. COD is a critical parameter that indicates the level of organic pollutants present in wastewater, making its reduction essential for environmental compliance and sustainability. Microbial fuel cells (MFCs) represent a promising method for treating IWW while simultaneously generating electricity. In these systems, microorganisms break down organic matter, facilitating COD removal. As they metabolize the pollutants, they release electrons, which can be captured as electrical energy. By integrating MFCs into IWW treatment processes, facilities can enhance COD removal efficiency while benefiting from renewable energy generation. This cluster highlights the potential of combining biological treatment methods with energy recovery strategies to create more sustainable solutions for managing IWW.

The eight clusters collectively illustrate a comprehensive framework for IWW treatment, integrating traditional and advanced methodologies. They emphasize the importance of effective pollutant removal through biological, chemical, and physical processes, while also highlighting innovative techniques such as EC, AOPs, and membrane technologies. Additionally, the research underscores the significance of optimizing treatment conditions using statistical and computational methods like RSM and ANNs. Sustainable strategies, including ozonation and Zero Liquid Discharge, further enhance resource recovery and environmental compliance. By incorporating microbial fuel cells, these clusters showcase a multifaceted approach that combines pollutant degradation with renewable energy generation, ultimately promoting efficiency and sustainability in wastewater management.

4. Challenges and recommendations for future works

4.1. Challenges

The current study identified several limitations regarding the treatment of IWW:

- The research relied exclusively on publications indexed in the Scopus database. This focus may exclude relevant studies from other databases or those published in non-English languages and regional journals. Consequently, the dataset might not accurately represent the global research landscape.
- The variety of methodologies used in different studies poses a significant challenge. This diversity prevents direct comparisons and general conclusions about the effectiveness of various IWW treatment methods, complicating the identification of best practices for IWW.
- While many studies highlight the effectiveness of IWW treatment methods, few provide a thorough assessment of their environmental impacts. Limited data on life cycle assessment (LCA) restrict a

comprehensive understanding of the ecological footprint associated with these methods.

- Most of the technologies explored in the reviewed literature are at the experimental or laboratory scale, with very limited real-world applications. Scaling these technologies up to an industrial level still faces many technical, financial, and logistical obstacles.

4.2. Recommendations for future work

To effectively address these challenges in IWW treatment and advance the field, the following recommendations are proposed:

- Focus should be directed toward creating scalable, eco-friendly technologies for IWW treatment. Emphasis on innovative methods such as EC, adsorption, and activated carbon can enhance environmental sustainability compared to traditional techniques. Research should aim to improve the efficiency, cost-effectiveness, and scalability of these technologies.
- Investigating sustainable practices that not only treat wastewater but also recover valuable resources, such as nutrients and energy, will be crucial. Research could explore circular economy approaches that view wastewater as a resource rather than a waste product.
- The exploration of novel materials, such as nanomaterials and bio-based adsorbents, can improve pollutant removal efficiency. Future studies should assess their effectiveness and scalability in real-world applications.
- Continued exploration of emerging technologies, such as membrane bioreactors and electrochemical methods, can provide new avenues for enhancing IWW treatment processes.
- Investigating the implications of policies and regulations on the adoption of advanced treatment technologies can help in understanding barriers and facilitators for implementation in various industries.
- Integrating wastewater valorization into circular economy frameworks at national and global levels is crucial. Clear guidelines for the collection, processing, and redistribution of wastewater across various industries should be established. Wastewater should be viewed not as a burden but as a valuable resource that can contribute to economic growth through the production of biofuels, bioplastics, animal feed, and other valuable products.
- Strengthening collaboration between academic institutions and industry partners is vital for translating laboratory research into large-scale applications. Such partnerships can drive innovation, particularly in refining treatment methodologies and enhancing the functional properties of treated wastewater.
- Comprehensive public awareness campaigns should be implemented to educate all stakeholders in the agricultural value chain—from farmers to consumers—about the importance of wastewater valorization. Training programs focused on sustainable practices, waste management, and the benefits of a circular economy should be developed to encourage active involvement in valorization initiatives.

By implementing these recommendations, the field of IWW treatment can make significant strides toward more effective, sustainable, and economically viable solutions.

5. Conclusion

A bibliometric analysis of IWW treatment research was carried out in this study. After filtering, 1714 articles from the Scopus database were subjected to bibliometric analysis using the VOSviewer software. Significant new developments in this area were made public. According to the bibliometric study, more than 59.7 % of the research on IWW treatment has been published in the previous five years, with a peak of 244 articles in 2022. This indicates that the need to treat IWW is

becoming more widely recognized. This trend highlights a strong concern for treating IWW and underscores the research community's awareness of the rising levels of IWW resulting from urbanization and pollution. To overcome these obstacles, there is an evident need for the creation of novel treatment technologies.

The Journal of Water Process Engineering, Desalination and Water Treatment, and Journal of Environmental Chemical Engineering are the three highest ranked scholarly journals that address the treatment of IWW, according to the results of the current study. The majority of research is carried out in relatively common fields with concentrations in energy, chemistry, and chemical engineering (66.69 %, 22.29 %, and 11.03 %, respectively). With contributions of 11.79 %, 10.44 %, and 3.4 %, respectively, India, China, and Iran made the biggest contributions to the field of IWW therapy. The University of Chinese Academy of Sciences made noteworthy contributions in this area with 7 publications and 74 citations. Additionally, Tianjin University's School of Environmental Science and Engineering has four publications and an astounding 273 citations, demonstrating the importance and impact of its research.

Co-occurrence and clustering were used to assess the author's IWW treatment terms. The most commonly used terms are "heavy metals," "electrocoagulation," "adsorption," "treatment," "wastewater," "industrial wastewater," "wastewater treatment," and "response surface methodology." The primary focus of this field's research is adequately defined by the keywords that were selected. The most prevalent contaminants found in IWW, such as dye, COD, and heavy metals, must be eliminated. Researchers are also concentrating on ways to remediate certain kinds of IWW, such wastewater from tanneries and textiles. The most popular treatment techniques for IWW, according to bibliometric study, are ozonation, activated carbon, EC, adsorption, and ceramic membranes.

CRedit authorship contribution statement

Motasem Y.D. Alazaiza: Formal analysis, Conceptualization. **Tharaa M. Alzghoul:** Writing – original draft. **Madhusudhan Bangalore Ramu:** Writing – review & editing. **Salem S. Abu Amr:** Writing – review & editing, Validation. **Mohammed F.M. Abushammala:** Writing – review & editing. **Dia Eddin Nassani:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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