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Review

Natural Coagulants for Sustainable Wastewater Treatment: Current Global Research Trends

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Abstract: Natural coagulants have gained significant attention as effective agents for wastewater treatment, particularly in the removal of heavy metals. This study conducts a comprehensive bibliometric analysis of 268 publications over the past decade, aiming to assess research trends and developments in the application of natural coagulants in wastewater management. The analysis reveals a marked increase in publication output, with the number of articles rising from just five in 2015 to fifty-one in 2024, indicating a growing global awareness and investment in sustainable wastewater treatment practices. "Environmental science" emerges as the leading discipline, accounting for 31.3% of the total publications. Notably, Malaysia is identified as the foremost contributor, with 60 publications and 1149 citations, followed by India and Brazil, highlighting the robust research activity in these regions. The study identifies key natural coagulants, such as Moringa oleifera and chitosan, which are frequently cited for their efficacy in reducing heavy metal concentrations and improving overall water quality. Leading funding organizations, such as the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior in Brazil, have significantly contributed to the growth of this field by financing numerous studies. Prominent journals, including the *Journal of Environmental Chemical Engineering* and *Water Research*, play a crucial role in disseminating research findings and advancing knowledge in this area. These publications are vital for sharing innovative methodologies and effective treatment solutions in the field of natural coagulants. Effective treatment methodologies identified in the literature include coagulation/flocculation and adsorption. The study highlights a variety of natural materials utilized for wastewater treatment, including plant-based coagulants derived from agricultural by-products, which not only address environmental concerns but also promote resource recovery.

Keywords: bibliometric analysis; eco-friendly processes; environmental impact; green chemistry; heavy metals; natural coagulants; sustainable wastewater treatment

Academic Editor: Antoni Sánchez

Received: 14 April 2025
Revised: 27 May 2025
Accepted: 28 May 2025
Published: 2 June 2025

Citation: Alazaiza, M.Y.D.; Alzghoul, T.M.; Nassani, D.E.; Bashir, M.J.K. Natural Coagulants for Sustainable Wastewater Treatment: Current Global Research Trends. *Processes* **2025**, *13*, 1754. https://doi.org/10.3390/pr13061754

1. Introduction

The rapid pace of industrialization, driven by population growth and increased consumer demand, has resulted in significant challenges related to wastewater management [1,2]. Industrial activities often generate wastewater contaminated with heavy metals and organic pollutants, posing serious risks to human health and the environment [1,3,4].

Heavy metals such as selenium (Se), nickel (Ni), molybdenum (Mo), manganese (Mn), iron (Fe), copper (Cu), cobalt (Co), and chromium (Cr) are non-biodegradable and can exhibit carcinogenic properties [5–7]. When these contaminants enter water bodies in excessive concentrations, they lead to severe health issues, disrupt ecological balance, and threaten biodiversity [8]. The presence of heavy metals in aquatic environments adversely affects drinking water supplies, agricultural practices, and aquatic life, underscoring the urgent need for effective treatment methods to remove these pollutants [3,9].

Efficiently separating and neutralizing unwanted heavy metal ions from wastewater remains a critical challenge in environmental pollution management [10]. Conventional treatment methods, such as electrochemical processes [11], ion exchange [12], and chemical precipitation [13], have been employed to address heavy metal contamination. However, these methods are often associated with significant drawbacks, such as high operational costs, toxicity to humans and the environment, significant energy consumption, corrosive and carcinogenic nature, alterations to the pH of treated water, and the production of hazardous, non-biodegradable sludge [14–16]. These issues necessitate the exploration of alternative approaches that can mitigate the adverse effects of chemical coagulants on ecosystems.

Coagulation/flocculation (C/F) is a widely used physiochemical treatment method that effectively removes suspended solids and resistant contaminants from wastewater [17,18]. This method involves neutralizing the charge of colloidal particles and promoting their aggregation into larger flocs, which can then be easily removed [19]. However, traditional chemical coagulants, such as Fe and Al salts, are associated with several drawbacks, including high costs, toxicity, significant pH alterations in treated water, and the generation of large volumes of hazardous sludge [20–22].

In recent years, there has been a paradigm shift towards sustainable wastewater treatment practices, encouraging industries to adopt natural substances in place of harmful chemicals [23]. This shift has led to decreased environmental impacts in terms of production, consumption, and secondary waste management [23]. Natural coagulants, derived from plant, animal, and microbial sources, have emerged as a promising alternative for heavy metal removal in wastewater treatment [3,19]. These coagulants are polyelectrolytes, which can be anionic, cationic, or neutral polymers [23]. They are not only safe and cost-effective but also possess the capacity to maintain the pH of the wastewater being treated without increasing the metal load during the process [24]. Additionally, natural coagulants generate lower volumes of sludge, significantly reducing disposal costs [23,24].

Industries, particularly in the agro-sector, produce substantial quantities of waste materials, such as fruit peels, seeds, and other by-products [25]. These materials often contain valuable bioactive compounds, and when not properly managed, they contribute to environmental degradation and resource wastage [12,26]. To address these issues, innovative approaches such as green extraction technologies are being developed to convert agro-waste into high-value secondary resources, aligning with the principles of a circular economy [27]. This valorization of agricultural waste not only enhances resource efficiency but also improves water quality and reduces environmental pollution.

Natural coagulants, derived from these agricultural byproducts, are biodegradable and environmentally friendly, contributing to waste reduction while enhancing treatment efficiency [19,28]. Research indicates that these coagulants can effectively neutralize charges in colloidal particles and promote their aggregation, achieving removal efficiencies comparable to those of traditional chemical coagulants [29,30]. Their integration into wastewater treatment processes addresses the limitations associated with chemical coagulants and promotes the sustainable use of resources [31]. However, several gaps in current research remain. Firstly, there is a lack of large-scale, real-world applications and regulatory frame-

works that support the adoption of natural coagulants in various contexts [23]. Secondly, while the effectiveness of natural coagulants has been demonstrated in laboratory settings, further studies are needed to assess their long-term performance, stability, and potential toxicity in real-world wastewater treatment scenarios [23,24].

The sustainability of natural coagulants is crucial for their acceptance in wastewater treatment. This sustainability encompasses social, environmental, and financial aspects [24]. Social acceptance relies on their ability to deliver results comparable to traditional coagulants [23]. Despite their natural origin, questions remain regarding the potential toxicity of organic coagulants in humans and the environment. Further research is needed to confirm their safety and optimize their application in wastewater treatment. In light of these challenges, it is essential to explore key areas, emerging trends, and future directions regarding natural coagulants in wastewater treatment research. This exploration aims to enhance understanding and inform regulatory initiatives, addressing the urgent need for further research to bridge existing knowledge gaps.

Bibliometric analysis is an effective method for systematically examining published literature, providing both quantitative and qualitative insights into scientific activities [32–34]. By utilizing statistical methods, bibliometric studies reveal patterns in research productivity across individuals, institutions, and countries [35–37]. Co-citation analysis further uncovers relationships among documents, facilitating the identification of new research frontiers [33]. This study specifically focuses on the Scopus database due to its comprehensive coverage of high-quality, peer-reviewed literature, ensuring the reliability and relevance of our analysis.

By employing bibliometric methods, this study aims to analyze the literature on natural coagulants in wastewater treatment over the past decade, emphasizing key developments and future trends. The analysis will assess publication trends, leading journals, and geographical research distributions while exploring contributions from prominent universities and identifying key influencers through co-citation networks. Highlighting the most cited works will clarify foundational studies and reveal gaps in the literature, suggesting new avenues for future research. Green chemistry plays a crucial role in this context by emphasizing the design of chemical processes that minimize hazardous substances and environmental impact. By incorporating green chemistry principles, the exploration of natural coagulants aligns with sustainable practices that benefit both the environment and public health.

2. Methods

2.1. Data Sources and Bibliometric Approach

This research employed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) as its methodology for the literature review, strictly following PRISMA guidelines while deliberately excluding meta-analysis techniques from our analysis. Bibliometric analysis serves as an essential tool in systematic literature reviews, facilitating the establishment of a comprehensive and reproducible database [27]. Its broad acceptance is attributed to its capability to provide an integrated perspective on research domains, outputs, organizations, and trends [18]. This approach is particularly effective for scrutinizing extensive academic data, clarifying the connections between journal citations, and generating insights into both established and emerging fields of study [18]. Furthermore, bibliometric analysis aids in advancing ongoing research and development, emphasizing its implications, which contributes to its popularity across diverse scientific disciplines [17].

To examine trends and developments concerning the use of natural coagulants in wastewater treatment for heavy metals removal, this study employed bibliometric analysis. Data were sourced from the Scopus database, covering the period from 2015 to December 2024. The selection of the Scopus database was based on its extensive reposi-

tory of pertinent published articles and its comprehensive coverage of high-quality, peer-reviewed literature [17]. This ensures the reliability and relevance of our analysis, making it an ideal choice for this research. The literature search utilized the following query string and keywords: "(TITLE-ABS-KEY (("Natural Coagulant") AND ("Wastewater Treatment" OR "Heavy Metals Removal")) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p"))). This methodological approach ensured a focused and relevant dataset for the analysis of current trends in the field.

Records identified totaled 339 articles. No duplicate entries were found within the time range of 2015–2024. The document types included articles and conference papers, with 66 documents classified as reviews (39), book chapters (13), conference reviews (4), books (9), and one retracted document. The language of the records was predominantly English, with 5 documents in other languages: Portuguese (3), Arabic (1), and Spanish (1). Following the extraction and organization of data from the Scopus database, we generated Comma-Separated Values (CSV) files for further analysis. To ensure the reliability and accuracy of the data during the selection process, we implemented a series of filtering procedures. Once the records were categorized and assessed, we performed a comprehensive review of source names, authors, funding sponsors, and their affiliations for each year. Additionally, we evaluated the quality of the documents by analyzing their titles, abstracts, and keywords. Incomplete or erroneous records were systematically discarded through a rigorous filtration process to enhance the integrity of the dataset. Consequently, we refined the dataset to include only journal articles and conference paper published in English, ultimately reducing the total count to 268 publications, as illustrated in Figure 1.

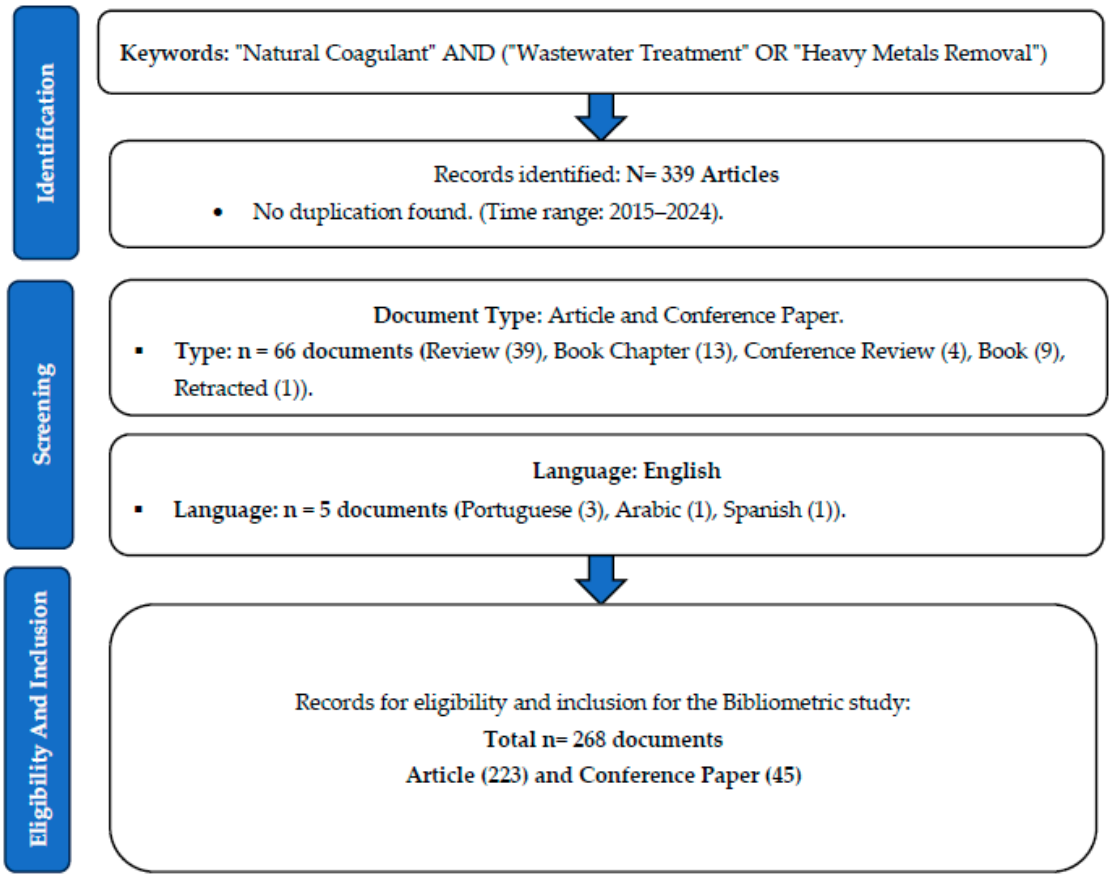

Figure 1. Flow diagram of the search method.

2.2. Visualization Procedure

In bibliometric research, the development and visualization of bibliometric maps significantly improve the clarity and identification of relationships among various sources. This approach facilitates the analysis of findings and aids researchers in understanding the structural dynamics of bibliometric results. To explore these findings and identify bibliometric patterns, we utilized VOSviewer version 1.6.20 for data processing. VOSviewer is an open-source, user-friendly tool specifically designed for the visualization and networking of bibliometric data [19].

The decision to use VOSviewer for our analysis stemmed from its ability to manage extensive networks effectively and its sophisticated text-mining capabilities [18]. This software allows for the identification of relationships and trends within the literature by generating bibliometric maps that visualize connections among selected articles [20]. A key advantage of VOSviewer is its dynamic label management, which adjusts to algorithmic requirements, thereby effectively displaying co-occurrences [20].

Our analysis concentrated on several primary aspects: the journals in which the articles were published, the author keywords employed in the papers, and the countries of origin. These factors provide a comprehensive overview of the research landscape, rendering them crucial for bibliometric investigations [21]. The analysis focused on key parameters, including publication counts, average normalized citations, and total link strength (TLS). These metrics are vital for assessing the visibility and impact of articles within the academic community [25].

Following the literature search, we identified a total of 268 documents, comprising both journal articles and conference papers. These publications originated from 124 unique sources. The body of literature on this subject was notably enriched by the contributions of 1014 authors representing 613 distinct institutions worldwide. Geographically, authors from 59 countries made significant contributions to this field of knowledge. The overall impact of these 268 documents is highlighted by a cumulative total of 4842 citations, emphasizing their importance within the academic community. Additionally, funding support was acknowledged from 124 sponsors. An analysis of the keywords provided by authors yielded further insights into the research themes, revealing a diverse array of 604 unique terms. Table 1 presents a summary of the key bibliometric findings related to the use of natural coagulants in wastewater treatment for the removal of heavy metals.

Table 1. Summary of key bibliometric results (2015–2024).

Description	Results
Documents (articles and conference articles)	268
Author keywords	604
Total citation	4842
Authors' affiliations	613
Document venues	124
Countries	59
Authors	1014
Funding sponsor	124

3. Results and Discussions

3.1. Publication Trend of the Use of Natural Coagulants in Wastewater Treatment

The annual publication count of scholarly articles serves as a critical metric for evaluating trends in scientific research development. Monitoring citation frequency provides essential insights into the quality and impact of these articles within the academic community. Data spanning from 2015 to December 2024 reveal a significant overall increase in the

number of publications concerning the use of natural coagulants in wastewater treatment, as illustrated in Figure 2.

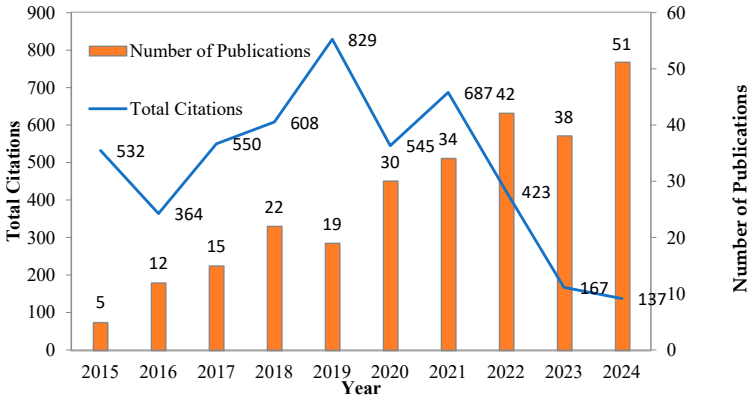

Figure 2. Analysis of annual trend of publication on use of natural coagulants in wastewater treatment for the last 9 years: authors' clarification based on Scopus data.

In 2015, only five articles were published, collectively receiving 532 citations. This notable citation count indicates that early research made substantial contributions to the field. By 2016, publications rose to 12, but citations decreased to 364, suggesting that newer works did not achieve the same recognition as earlier contributions. The trend continued into 2017, with 15 articles published and accumulating 550 citations, reaffirming sustained interest in the topic. In 2018, the field expanded further, resulting in 22 articles and 608 citations, demonstrating ongoing momentum in research efforts.

In 2019, despite a decrease in publications to 19, this year achieved the highest citation count of 829, underscoring the impact of those specific articles. The upward trend persisted into 2020, with 30 articles published and 545 citations, indicating a successful balance between quantity and quality. This positive trajectory continued in 2021, with 34 articles garnering 687 citations, reflecting high-quality output.

However, a notable decline was observed in 2022, where 42 articles resulted in only 423 citations. This may indicate a saturation of the topic or a change in scholarly focus. The following year, 2023, saw 38 publications accompanied by a significant drop in citations to 167, suggesting that newer research struggled to achieve the same impact as earlier studies. Finally, in 2024, while the count peaked at 51 articles, citations fell further to 137, implying a lack of recognition for recent contributions.

Overall, the data reveal an upward trajectory in research volume, yet the fluctuations in citation counts highlight varying impacts over time. The decline in citations in recent years underscores the need for further exploration of factors influencing visibility and recognition in this field. Addressing these challenges is essential for ensuring that new research continues to advance the understanding of natural coagulants in wastewater treatment effectively.

The bibliometric analysis of document types reveals a diverse landscape of research outputs related to the use of natural coagulants in wastewater treatment (Figure 3). Among the total documents analyzed, 223 are research articles, accounting for 65.8% of the contributions, while conference papers comprise 45 documents (13.3%). Other formats, such as review articles (39 or 11.5%), book chapters (13 or 3.8%), conference reviews (four or 1.2%), books (nine or 2.7%), retracted articles (one or 0.3%), and non-English language documents (five or 1.5%), represent a smaller fraction of the total publications. Given that research articles and conference papers are the most significant contributors to the literature in this field, they were selected for detailed analysis, while the remaining document types were

excluded. This focus underscores the importance of original research and ongoing scholarly discourse in advancing knowledge about natural coagulants in wastewater treatment.

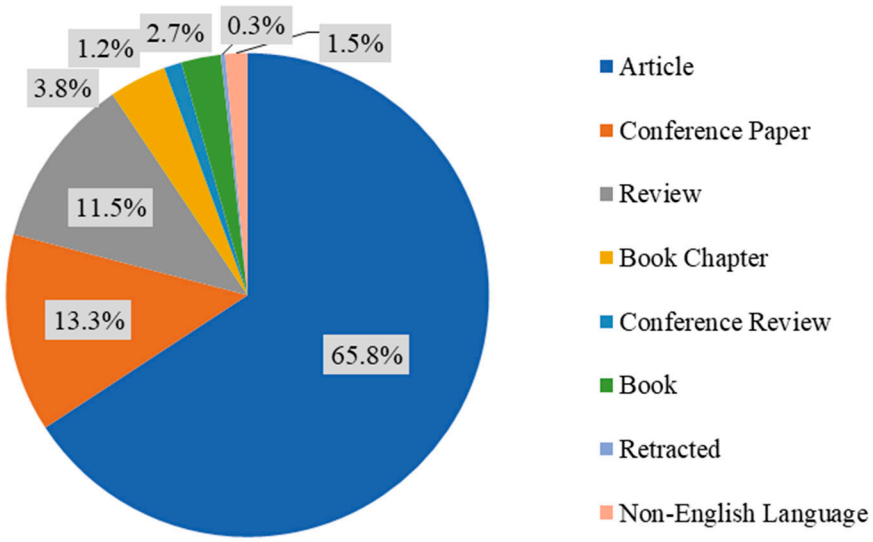

Figure 3. Document type percentage of reports for use of natural coagulants in wastewater treatment for heavy metal removal.

The predominance of research articles indicates that original research is the primary mode of knowledge dissemination in this area. This finding suggests that the study of natural coagulants is an actively evolving field, driven by continuous experimental investigations that enhance our understanding. Research articles serve as critical vehicles for knowledge development, delivering empirical data and showcasing methodological innovations that contribute to the growth of the field. Conference papers, while less numerous, play a vital role in summarizing recent findings and highlighting emerging trends. They facilitate immediate exchanges of ideas and preliminary results, essential for fostering collaboration and innovation within the scientific community. This dynamic exchange allows researchers to stay updated on the latest developments and identify opportunities for further exploration.

The relatively low representation of other document types, such as book chapters and editorials, indicates that research on natural coagulants has not yet been extensively compiled in traditional book formats. This may be attributed to the rapid pace of research in the field, which often necessitates the swift publication of findings in journals rather than the lengthier processes associated with book publications. Moreover, the absence of industrial reports and patents highlights a significant gap between academic research and practical application. Despite ongoing efforts in the academic sphere, there remains a challenge in translating these findings into industrial contexts.

Overall, the analysis emphasizes the active engagement in research on natural coagulants, while also pointing to areas for improvement in bridging the connection between academic findings and industrial application. The focus on articles and conference papers reflects their critical role in advancing this field of study.

The analysis of subject areas related to the use of natural coagulants in wastewater treatment for heavy metal removal reveals a diverse and interdisciplinary landscape of research. As shown in Figure 4, the dominant field is environmental science, with 173 documents (31.3%), highlighting the primary focus on addressing environmental issues through innovative treatment methods. This substantial representation underscores the critical importance of developing sustainable solutions for heavy metal removal, a pressing environmental concern.

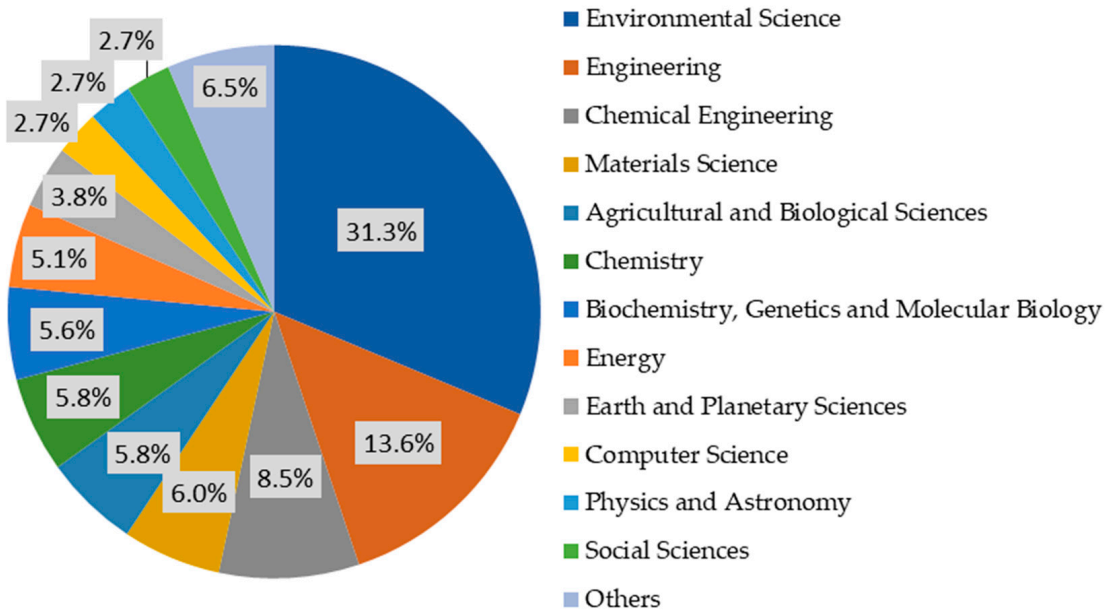

Figure 4. Subject area distribution of research on use of natural coagulants in wastewater treatment for heavy metal removal.

Following environmental science, engineering ranks second with 75 documents (13.6%), indicating a significant emphasis on the technical aspects of implementing natural coagulants in wastewater treatment processes. This area encompasses various engineering disciplines, focusing on optimizing treatment systems and designing effective processes that can be scaled for real-world applications. Chemical engineering is also noteworthy, contributing 47 documents (8.5%). This field is essential for refining the chemical processes involved in the treatment of wastewater, particularly in maximizing the efficiency and effectiveness of natural coagulants. Research in this area often explores the interactions between coagulants and contaminants, aiming to enhance removal rates while minimizing costs and environmental impact.

Materials science accounts for 33 documents (6%), reflecting the interest in developing and characterizing new materials that can function as natural coagulants. This subject area emphasizes the properties and performance of these materials in wastewater treatment, contributing to the advancement of sustainable practices in water treatment technology. Agricultural and biological sciences, as well as chemistry, each contribute 32 documents (5.8%). The presence of these fields indicates the potential for natural coagulants derived from agricultural by-products, linking wastewater treatment with resource recovery and sustainable agriculture. Moreover, the intersection of chemistry with environmental science emphasizes the need for chemically optimized solutions that align with sustainable practices.

Biochemistry, genetics, and molecular biology contribute 31 documents (5.6%), underscoring the relevance of molecular approaches in understanding the mechanisms by which natural coagulants interact with heavy metals. This knowledge can lead to enhanced coagulant formulations and improved treatment efficiencies. Energy, earth and planetary sciences, computer science, physics and astronomy, and social sciences are represented with lower percentages, ranging from 2.7% to 5.1%. These areas highlight the broader implications of wastewater treatment technologies, including energy recovery, environmental impact assessments, computational modeling of treatment processes, and the social dimensions of sustainable water management. Finally, the "Others" category, which encompasses various fields such as medicine, pharmacology, and business, includes 36 documents (6.5%). This

diversity reflects the multifaceted nature of wastewater treatment research, indicating that the implications of using natural coagulants extend beyond environmental science into areas such as public health, economic viability, and interdisciplinary collaboration.

Overall, the distribution of subject areas illustrates the interdisciplinary nature of research on natural coagulants in wastewater treatment for heavy metals removal. The predominance of environmental science and engineering highlights the urgent need for innovative and sustainable solutions to pressing environmental challenges. Future research should continue to bridge these disciplines, fostering collaboration that can lead to the development of effective, scalable, and sustainable wastewater treatment technologies.

3.2. Co-Citation Network of Authors in Use of Natural Coagulants in Wastewater Treatment

Co-citation author network analysis serves as a robust bibliometric approach for systematically charting existing literature [26]. This method identifies authors who are frequently cited together, illuminating the conceptual frameworks and thematic relationships within a particular research area. In our research, we employed VOSviewer to conduct an in-depth co-citation network analysis focused on the utilization of natural coagulants in wastewater treatment for heavy metal removal. Our findings reveal the leading authors, along with their publication counts and total citation metrics.

Table 2 presents a comprehensive overview of leading researchers in the field of natural coagulants for wastewater treatment, highlighting both their publication output and citation impact. The Matthew Effect, which suggests that established authors tend to receive more recognition and resources due to their higher volume of publications, is evident in this analysis. This phenomenon can create a disparity in visibility and influence within the academic community.

Table 2. Co-occurrence map of researcher collaboration (2015–2024) in natural coagulants for wastewater treatment: publication count and citation impact.

Author	No. of Publications	Author	Total Citations
Alazaiza, M.Y.D.,	12	Palácio, S.M.,	465
Abujazar, M.S.S.,	10	Veit, M.T.,	377
Veit, M.T.,	10	Fagundes-klen, M.R.,	355
Kristianto, H.,	9	Bergamasco, R.,	351
Abu Amr, S.S.,	8	Dotto, J.,	325
Bergamasco, R.,	8	Oliveira, V.M.,	210
Fagundes-klen, M.R.,	8	Geraldino, H.C.I.,	210
Karaağaç, S.U.,	8	Garcia, J.C.,	210
Palácio, S.M.,	8	Freitas, T.K.F.S.,	210
Prasetyo, S.,	8	Fávaro, S.I.,	210
Sugih, A.K.,	8	De Souza, M.T.F.,	210
Ismail, N.,	7	Almeida, V.C.,	210

Table 2 is divided into two distinct categories: the first category lists the researchers with the highest number of published papers, while the second category highlights those with the highest citation counts. Each category is presented separately, allowing for the possibility that an author may appear in both lists or in only one. This separation emphasizes the different metrics of success in academia: publication output, which reflects the volume of research contributions, and citation impact, which indicates the influence and recognition of those contributions within the academic community.

Our analysis reveals a group of prominent researchers who have significantly advanced the literature on the use of natural coagulants in wastewater treatment for heavy metal removal. The first section of the table focuses on the researchers with the high-

est number of publications. Leading the list is Alazaiza, M.Y.D., with 12 publications, indicating a strong commitment to this research area. Following closely are Abujazar, M.S.S. and Veit, M.T., both with 10 publications each, demonstrating substantial productivity. Other noteworthy contributors include Kristianto, H., with nine publications, and a group of authors—Abu Amr, S.S., Bergamasco, R., Fagundes-Klen, M.R., Karaağaç, S.U., Palácio, S.M., Prasetyo, S., and Sugih, A.K.—each with eight publications. This section underscores the active engagement of these researchers in advancing the literature on natural coagulants.

In terms of citations, Palácio, S.M. emerges as the most-cited author with a total of 465 citations, reflecting the significant impact of the work on the field. Veit, M.T. follows with 377 citations, and Fagundes-Klen, M.R. has 355 citations, indicating their influential contributions as well. Other authors such as Bergamasco, R. (351 citations) and Dotto, J. (325 citations) also demonstrate strong citation records, which suggest that their research is widely recognized and utilized within the academic community. Moreover, the table includes several authors who have each accumulated 210 citations. These researchers—Oliveira, V.M., Geraldino, H.C.I., Garcia, J.C., Freitas, T.K.F.S., Fávaro, S.I., De Souza, M.T.F., and Almeida, V.C.—share this citation count, suggesting that their work has been similarly acknowledged within the academic literature. This level of citation implies that their contributions are significant and impactful, even if their publication output may not match that of the leading authors.

This analysis highlights a dynamic research landscape characterized by a blend of prolific authors and those whose work garners substantial recognition through citations. The findings underscore the importance of both publication output and citation impact in shaping the discourse surrounding natural coagulants in wastewater treatment. This interplay between productivity and recognition is crucial for understanding the evolution of research in this vital area of environmental science, as it reveals the diverse contributions that collectively enhance knowledge and drive innovation in wastewater treatment methodologies.

3.3. Countries Distribution of Use the Natural Coagulants in Wastewater Treatment

The bibliometric analysis of leading countries in research on natural coagulants for wastewater treatment, as summarized in the Table 3, provides valuable insights into the contributions of various nations in this critical field. The data encompass essential statistics, including publication counts and citation numbers, reflecting each country's commitment to advancing knowledge in this area.

Malaysia emerges as the foremost contributor, with an impressive total of 60 publications and 1149 citations. This substantial output highlights Malaysia's robust research capabilities and its leading role in the study of natural coagulants for heavy metal removal in wastewater treatment. Following closely is India, which ranks second with 40 publications and 542 citations, underscoring its significant presence in the research landscape. Brazil is also a noteworthy player, having produced 39 publications and garnered 1122 citations. This indicates a strong scholarly focus on addressing environmental challenges associated with wastewater management. Indonesia follows with 24 publications and 378 citations, reflecting its growing interest in utilizing natural coagulants in wastewater treatment processes.

In the Arab region, Oman contributes 16 publications and 61 citations, demonstrating its commitment to sustainable wastewater treatment practices. Turkey, which straddles both Europe and Asia, adds another dimension with 12 publications and 193 citations. Palestine, despite a smaller output of 10 publications and 41 citations, still plays a role in the discourse surrounding wastewater treatment. Iraq, with eight publications and 26 citations, illustrates a burgeoning interest in this field, alongside Morocco, which has

seven publications and 164 citations, and Spain, which contributes seven publications with 85 citations. Colombia also has seven publications, but with a lower citation count of 30.

Table 3. Leading 13 countries through collaboration publishing on natural coagulants in wastewater treatment for heavy metal removal research (ranked by total link strength (TLS)).

Country	Cluster	TLS	Documents	Citations
Malaysia	1	6515	60	1149
Turkey	2	4888	12	193
Oman	2	4592	16	61
Palestine	2	4173	10	41
Indonesia	1	2312	24	378
Brazil	1	2155	39	1122
Iran	1	2150	13	454
India	1	2051	40	542
China	1	1471	8	157
Morocco	1	1017	7	164
Colombia	1	760	7	30
Spain	1	387	7	85
Iraq	1	179	8	26

Overall, Table 3 illustrates a diverse international landscape in the research on natural coagulants for wastewater treatment. The prominence of Malaysia, India, and Brazil indicates established research infrastructures and substantial scholarly activity in these regions. Meanwhile, the increasing involvement of Arab countries suggests an emerging interest and potential for growth in this area. The findings underscore the importance of international collaboration, particularly between Arab and European nations, in facilitating the exchange of knowledge and methodologies necessary for developing effective and sustainable wastewater treatment solutions. Such partnerships can leverage the strengths of each region, ultimately addressing the complex challenges posed by wastewater management and enhancing environmental sustainability.

Figure 5 highlights the critical role of global networks in facilitating the exchange of knowledge concerning the use of natural coagulants in wastewater treatment. Given the multidisciplinary nature of this research area, international collaboration is essential for addressing complex challenges such as water scarcity and the need for efficient resource recovery. Countries that lead in this field typically possess well-established natural coagulant industries and high-quality research institutions, enabling them to make significant contributions to the advancement of wastewater treatment technologies.

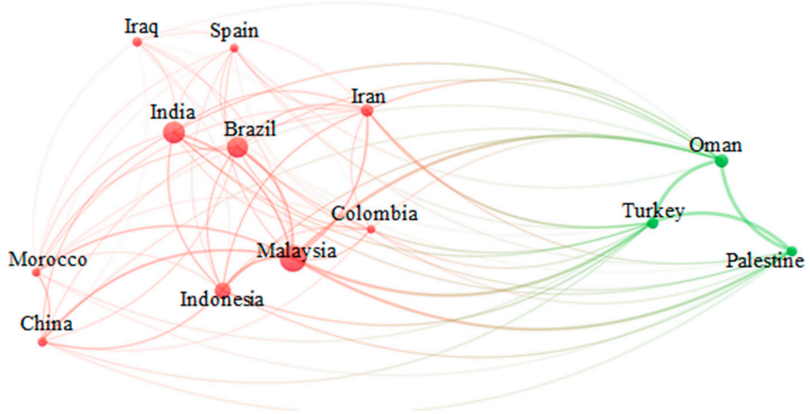

Figure 5. Mapping visualization of countries in the investigation of the countries in natural coagulants in wastewater treatment research.

Malaysia's dominance in research output is largely due to its strategic investments in wastewater treatment technologies and its ability to harness local natural resources effectively. This positions Malaysia as a key player in the development of innovative solutions for wastewater management. India, with its historical emphasis on sustainable practices, has also focused intensively on optimizing natural coagulants to maximize their effectiveness in treatment processes. Brazil's contributions stem from its rich biodiversity, particularly the vast resources available in the Amazon region, which provide a variety of natural materials applicable for coagulant development.

In Figure 5, the nodes represent various elements within a keyword co-occurrence network, with their shapes and positions indicating the likelihood of co-occurrence among these elements. The analysis reveals four distinct clusters, each represented by a different color, which reflect various topics related to the application of natural coagulants in wastewater treatment. The size of the nodes corresponds to their frequency of occurrence, while the thickness of the connections between nodes signifies the strength of their relationships.

Furthermore, the VOSviewer map depicted in Figure 5 illustrates the collaborative networks among nations, emphasizing the interconnectedness of research efforts in this area. The contributions of these leading countries in the field of natural coagulants are particularly relevant in the context of addressing water scarcity and enhancing resource recovery from wastewater. By focusing on the development and application of natural coagulants, these nations not only advance wastewater treatment methodologies but also promote sustainable practices in water management [17,27].

In summary, the collaborative initiatives among these countries underscore the importance of sharing knowledge and resources in the pursuit of effective solutions for wastewater treatment. This is essential for tackling the pressing environmental challenges associated with water scarcity and resource sustainability. To identify the leading institutions engaged in research on natural coagulants for wastewater treatment, a comprehensive mapping exercise was conducted using data extracted from 268 publications available in the Scopus database, as illustrated in Figure 6.

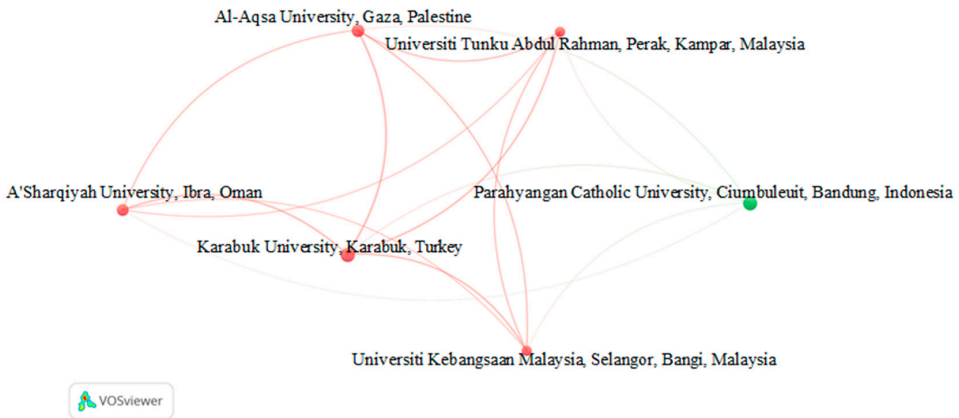

Figure 6. A network visualization representing the primary universities involved in research on the use of natural coagulants in wastewater treatment.

The initial dataset primarily provided affiliations categorized as departments or colleges, rather than clearly indicating the specific universities or research institutions. Consequently, it was essential to reorganize this information to accurately reflect the involvement of the respective universities or research institutions, as detailed in Table 4. In summary, the collaborative initiatives among these countries underscore the importance of sharing knowledge and resources in the pursuit of effective solutions for wastewater treatment. This is essential for tackling the pressing environmental challenges associated with water

scarcity and resource sustainability. To identify the leading institutions engaged in research on natural coagulants for wastewater treatment, a comprehensive mapping exercise was conducted using data extracted from 268 publications available in the Scopus database, as illustrated in Figure 6.

Table 4. Top 6 universities based on authors' affiliation with a minimum of 4 published documents.

Affiliation	Department	Country	TLS	No. of Documents	Total Citations
Karabuk University	Department of Environmental Engineering, Faculty of Engineering	Karabuk, Turkey	2397	7	29
Al-Aqsa University	Al-Aqsa Community Intermediate College	Gaza, Palestine	1951	6	21
Universiti Kebangsaan Malaysia	Department of Civil Engineering, Faculty of Engineering and Built Environment	Selangor, Malaysia	1583	4	20
Universiti Tunku Abdul Rahman	Department of Environmental Engineering, Faculty of Engineering and Green Technology	Kampar, Malaysia	1583	4	20
A'Sharqiyah University	Department of Civil and Environmental Engineering, College of Engineering	Ibra, Oman	1313	5	14
Parahyangan Catholic University	Department of Chemical Engineering, Faculty of Industrial Technology	Bandung, Indonesia	149	7	150

Among the leading institutions conducting research on the use of natural coagulants in wastewater treatment, Parahyangan Catholic University in Ciumbuleuit, Bandung, Indonesia stands out as the institution with the highest number of citations, achieving a total of 150 citations from its seven publications. This significant citation count reflects the high regard for its research contributions in the field, as illustrated in Table 4. In terms of publication output, Karabuk University in Karabuk, Turkey also has seven publications but has garnered only 29 citations. This indicates that while it has a strong publication record, the impact of its research is not as widely recognized as that of Parahyangan Catholic University. Following these institutions, Al-Aqsa University in Gaza, Palestine has produced six publications with 21 citations. Universiti Kebangsaan Malaysia, through its Department of Civil Engineering, has published four articles and received 20 citations, indicating its important role in the field, particularly regarding natural coagulants. Similarly, Universiti Tunku Abdul Rahman has also published four articles with 20 citations, maintaining a significant influence within the academic community. Lastly, A'Sharqiyah University in Ibra, Oman has published five articles with 14 citations, contributing to the overall understanding of natural coagulants in wastewater treatment.

Overall, the institution with the highest number of publications is Karabuk University, and Parahyangan Catholic University is recognized for having the highest number of citations, highlighting the varying levels of research output and impact among these institutions.

3.4. Leading Journals on Use of Natural Coagulants in Wastewater Treatment Research

Table 5 provides a comprehensive overview of the top 11 journals related to research on natural coagulants in wastewater treatment for heavy metals removal. This summary includes key metrics such as the number of publications and total citations for each journal, highlighting their contributions to the field.

Table 5. The top 11 journals related to natural coagulants in wastewater treatment for heavy metal removal research.

Journal	TLS	No. of Documents	No. of Citations
Desalination and Water Treatment	500	19	131
Industrial Crops and Products	438	7	637
Journal of Environmental Chemical Engineering	404	9	347
Water, Air, and Soil Pollution	368	11	135
Journal of Water Process Engineering	324	9	243
International Journal of Environmental Science and Technology	258	7	80
Environmental Science and Pollution Research	202	6	67
Environmental Technology (United Kingdom)	198	6	55
Water (Switzerland)	155	6	78
IOP Conference Series: Earth and Environmental Science	65	12	89
Journal of Physics: Conference Series	20	6	11

Based on the data presented in Table 5, an analysis of the most influential journals reveals significant insights regarding their impact in the field of natural coagulants in wastewater treatment for heavy metals removal. *Industrial Crops and Products* emerges as a leading journal with seven publications and an impressive total of 637 citations. This high citation count indicates that the research published in this journal is highly regarded and frequently referenced, reflecting its substantial influence on the development of natural coagulants. Following closely is the *Journal of Environmental Chemical Engineering*, which has published nine articles and received 347 citations. This journal is pivotal for advancing knowledge at the intersection of environmental chemistry and engineering, particularly concerning the application of natural coagulants in wastewater treatment processes.

The *Journal of Water Process Engineering* also contributes significantly to the field, with nine publications and 243 citations. Its focus on innovative engineering solutions for water treatment enhances its relevance among researchers and practitioners. *Water, Air, and Soil* Pollution has produced 11 publications and garnered 135 citations, emphasizing its role in addressing various environmental pollution issues through effective treatment strategies. Similarly, the *IOP Conference Series: Earth and Environmental Science* has 12 articles with 89 citations, indicating its function as a platform for disseminating research findings in environmental sciences.

Another noteworthy journal is *Desalination and Water Treatment*, which has 19 publications and 131 citations. Its extensive output highlights its importance in the field, even though its citation count is relatively lower compared to other journals like *Industrial Crops and Products*. Additionally, *International Journal of Environmental Science and Technology* has seven publications with 80 citations, and *Environmental Science and Pollution Research* has six publications and 67 citations, both contributing valuable research to the understanding of natural coagulants. *Environmental Technology* (United Kingdom) and *Water* (Switzerland) each have six publications, with total citations of 55 and 78, respectively, indicating their contributions to the discourse on wastewater treatment technologies. Finally, the *Journal of Physics: Conference Series* has published six articles, but with a modest total of 11 citations, suggesting that while it adds to the body of knowledge, its impact may be limited compared to other journals in this analysis.

Overall, while *Industrial Crops and Products* leads in citation impact, journals like the *Journal of Environmental Chemical Engineering* and the *Journal of Water Process Engineering* are also vital to the field. These publications collectively emphasize the critical role of research

on natural coagulants in wastewater treatment, reflecting the ongoing advancements and the importance of sustainable practices in addressing heavy metal removal.

Figure 7 illustrates that 11 of the sources located fulfilled these criteria.

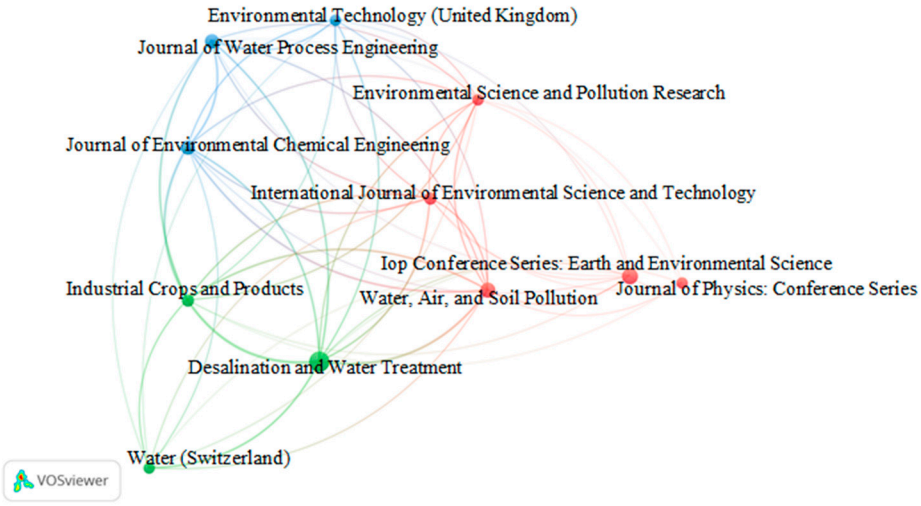

Figure 7. Networking visualization of journals published in 2015–2024 that have more than 6 documents related to natural coagulants in wastewater treatment research in 2015–2024.

This analysis highlights a robust network of high-impact journals dedicated to research on natural coagulants in wastewater treatment, specifically concerning the removal of heavy metals. These journals are essential platforms for disseminating significant research findings, and the varying publication counts among them reflect their influence and specific areas of focus.

As shown in Figure 8, The leading journal, *Desalination and Water Treatment*, has published a total of 19 articles. Its publication trend shows notable activity, particularly in recent years, with four articles in 2016, followed by one in 2017, one in 2018, and a resurgence with four in 2022, five in 2023, and four in 2024. This pattern indicates a growing urgency in addressing wastewater treatment issues and highlights the journal's pivotal role in advancing knowledge in this critical field. Following closely, *IOP Conference Series: Earth and Environmental Science* has contributed 12 publications, with a varied output over the years. The journal published one article in 2016, one in 2019, two in 2020, and saw a peak in 2021 with four articles. Its output in 2023 and 2024 remained steady with two articles each year, showcasing its importance in facilitating discussions on environmental science.

Water, Air, and Soil Pollution has produced eleven articles, primarily concentrated in a few years: two articles in 2017, two in 2020, two in 2021, and another two in 2022, with one article in 2024. This consistent contribution emphasizes the journal's role in addressing environmental pollution issues through rigorous research. Both the *Journal of Environmental Chemical Engineering* and the *Journal of Water Process Engineering* have each published nine articles. The former shows a publication trend with four articles in 2018, two in 2020, and one each in 2021, 2022, and 2023. Meanwhile, the latter has a more recent focus, with two articles in 2020, three in 2021, and a notable increase to four in 2024, reflecting an active engagement with current wastewater treatment challenges.

Overall, the analysis of publication counts among these key journals illustrates the diverse opportunities for researchers to engage in meaningful contributions to the field. The prominence of these publications emphasizes the growing urgency and commitment to addressing the challenges associated with wastewater management and heavy metal removal, reflecting an ongoing dedication to improving environmental health and sustain-

ability. Collectively, these trends indicate a vibrant research landscape that continues to evolve and adapt to emerging environmental concerns.

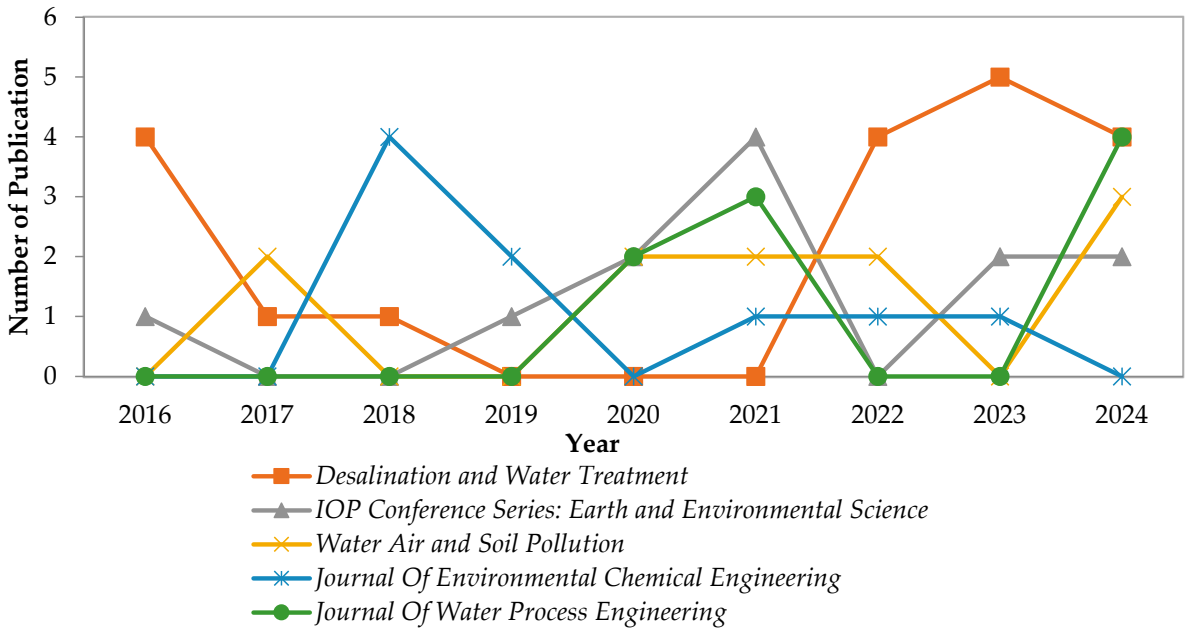

Figure 8. Publication statistics on the use of natural coagulants in wastewater treatment.

3.5. Key Funding Sources Supporting the Application of Natural Coagulants in Wastewater Treatment Research

The analysis of funding sponsors related to research on the application of natural coagulants in wastewater treatment reveals significant insights into the financial backing for this critical area of study. Figure 9 illustrates a diverse range of institutions contributing to the advancement of this field.

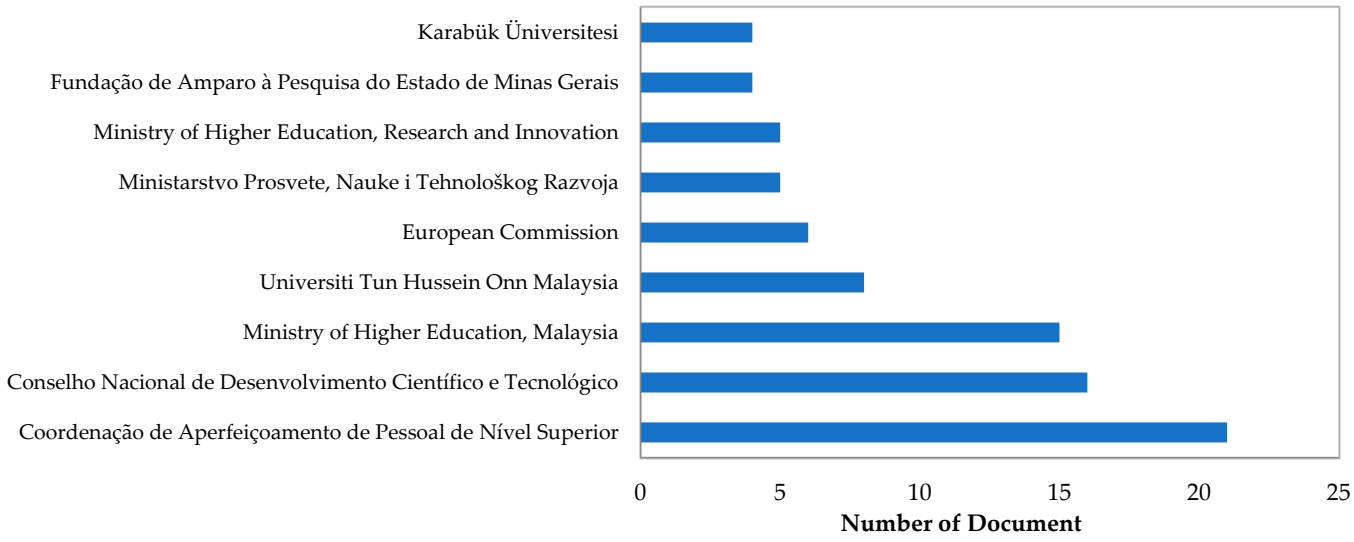

Figure 9. Top 9 funding sponsors for the application of natural coagulants in wastewater treatment research.

As shown in Figure 9, leading the list is the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior with 21 publications, indicating a strong commitment to enhancing research capabilities and promoting higher education in Brazil. This substantial support underscores the importance of natural coagulants in addressing wastewater treatment

challenges. Following closely is the Conselho Nacional de Desenvolvimento Científico e Tecnológico, which has funded 16 publications. This organization plays a crucial role in financing scientific research in Brazil, reflecting its dedication to environmental studies and innovation in wastewater management.

The Ministry of Higher Education, Malaysia has also made significant contributions, supporting 15 publications. This involvement highlights Malaysia's recognition of the importance of sustainable practices in wastewater treatment and its commitment to fostering research in this area. Universiti Tun Hussein Onn Malaysia has contributed eight publications, demonstrating the role of academic institutions in advancing knowledge and techniques related to the use of natural coagulants in wastewater processes.

The European Commission has supported six publications, indicating its involvement in addressing environmental issues at a continental level, particularly in the context of water treatment solutions. Additionally, the Ministarstvo Prosvete, Nauke i Tehnološkog Razvoja and the Ministry of Higher Education, Research and Innovation have each funded five publications. Their support reinforces the importance of governmental backing for research initiatives that aim to improve environmental health and sustainability. Finally, both Fundação de Amparo à Pesquisa do Estado de Minas Gerais and Karabük Üniversitesi have contributed four publications each, reflecting the contributions of regional research institutions and foundations in driving forward the agenda of sustainable wastewater management.

Overall, this funding landscape highlights the diverse sources of financial support driving research on the application of natural coagulants in wastewater treatment. The significant contributions from Brazilian and Malaysian institutions, alongside the involvement of the European Commission, illustrate a global commitment to understanding and addressing the challenges posed by wastewater contamination. This collaboration across various sectors is essential for advancing knowledge and developing effective management strategies for sustainable practices in wastewater treatment.

3.6. Most Influential Publications Related the Application of Natural Coagulants in Wastewater Treatment Research

Citation analysis serves as a vital method for understanding the intellectual landscape of a particular academic discipline, especially by revealing how one publication references another. This analytical approach allows researchers to identify seminal works within a specific field, while also facilitating the exploration of citation trends and patterns [1,28]. In the context of this study, we conducted a citation analysis of scholarly articles focusing on the application of natural coagulants in wastewater treatment.

Presented in Table 6, the top 24 most-cited documents in this area highlight the studies that have significantly advanced the field. This table ranks these influential publications according to their citation counts, providing critical insights into the methodologies utilized and the key findings that have fundamentally shaped the ongoing discourse surrounding the application of natural coagulants in wastewater treatment research. By examining these highly cited works, we can better understand the foundational research that has influenced current practices and future directions in the field, thereby underscoring the importance of citation analysis in mapping the evolution of knowledge in wastewater treatment.

Natural coagulants, derived from plant sources, have gained significant attention in wastewater treatment due to their effectiveness and environmental benefits. This analysis explores their mechanisms of action, applications, and limitations, emphasizing their alignment with the principles of green chemistry. The increasing use of natural coagulants reflects a growing awareness of sustainable practices in wastewater management, particularly in developing regions where access to synthetic alternatives may be limited.

Natural coagulants function by neutralizing the charges on suspended particles in wastewater. This neutralization enables the aggregation of these particles, facilitating

their removal through sedimentation [2,15]. The mechanisms involved include charge neutralization and bridging, where coagulants form links between particles, enhancing floc formation. However, the performance of natural coagulants can be influenced by several factors, including optimal dosage, pH levels, and the specific characteristics of the wastewater [23,24]. While they are capable of effectively reducing pollutants, the efficiency of removal can vary significantly based on the type of coagulant used and the specific contaminants present. Despite the general affordability of natural coagulants compared to synthetic options, their availability can still be a limiting factor, particularly in regions where specific plant sources may not be easily accessible. This highlights the importance of local sourcing and cultivation of these materials to ensure sustainability and reliability in wastewater treatment practices.

Among the highly cited studies, Moringa oleifera is particularly effective for removing contaminants from wastewater generated by textile and municipal sources. It effectively reduces color and chemical oxygen demand (COD), making it suitable for both types of applications [3,38]. Okra mucilage, on the other hand, excels in its low dosage requirements, showcasing excellent removal rates for color and turbidity, particularly in textile wastewater (TWW). Its biodegradable nature further enhances its appeal in sustainable practices [9], while Alyssum mucilage has shown promise in treating oily–saline wastewater [32]. Potato starch has also been utilized for treating TWW [30]. Guar gum has been employed in landfill leachate treatment [31].

Cassia obtusifolia seed gum, while effective, often requires the addition of aluminum sulfate to maximize its coagulation potential. This combination can be beneficial in industrial contexts but introduces synthetic chemicals into the process [39]. Furthermore, Aloe Vera and cactus were studied by Muruganandam et al. [33] as natural coagulants for treating tannery effluent. In the realm of municipal wastewater treatment, various plant-based coagulants have been evaluated, including banana peel powder, banana stem juice, papaya seed powder, and neem leaf powder [34]. Other natural coagulants mentioned include eggshells, which were investigated for industrial wastewater treatment [35], and chitosan, a natural biopolymer studied for its effectiveness in removing color and turbidity from industrial wastewater [36]. Chickpea coagulants present a promising option for agricultural wastewater treatment, achieving good turbidity removal and emphasizing local availability and cost-effectiveness [40].

The effectiveness of banana pith as a natural coagulant for polluted river water was demonstrated [41]. Ocimum basilicum mucilage was investigated for dye removal from TWW [42], and finally, nopal pectin was explored as a dual C/F agent for heavy metal removal from synthetic wastewater [4]. Collectively, these natural coagulants represent a diverse array of plant-based materials that have been studied for their potential in effectively treating wastewater and removing various contaminants. Overall, natural coagulants represent a sustainable alternative to synthetic chemicals in wastewater treatment, aligning closely with the principles of green chemistry. Understanding the unique strengths and applications of each type allows for informed decisions in wastewater management. Continued research is essential to optimize their use and address challenges, ultimately facilitating broader adoption of these eco-friendly solutions across various industries.

Table 6. The top 24 most-cited documents related the application of natural coagulants in wastewater treatment research.

First Author	Year	Document Title	Journal	Citations	Ref.
Dotto, J.,	2019	Performance of different coagulants in the coagulation/flocculation process of textile wastewater.	*Journal of Cleaner Production*	325	[2]
Freitas, T.K.F.S.,	2015	Optimization of coagulation-flocculation process for treatment of industrial textile wastewater using okra (*A. esculentus*) mucilage as natural coagulant.	*Industrial Crops and Products*	210	[9]
Shan, T.C.,	2017	The use of Moringa oleifera seed as a natural coagulant for wastewater treatment and heavy metals removal.	*Applied Water Science*	151	[3]
Shak, K.P.Y.,	2015	Optimized use of alum together with unmodified *Cassia obtusifolia* seed gum as a coagulant aid in treatment of palm oil mill effluent under natural pH of wastewater	*Industrial Crops and Products*	130	[39]
Kakoi, B.,	2016	Banana pith as a natural coagulant for polluted river water.	*Ecological Engineering*	107	[41]
Shamsnejati, S.,	2015	Mucilaginous seed of *Ocimum basilicum* as a natural coagulant for textile wastewater treatment	*Industrial Crops and Products*	102	[42]
Ibarra-Rodríguez, D.,	2017	Capacity of 'nopal' pectin as a dual coagulant-flocculant agent for heavy metals removal.	*Chemical Engineering Journal*	85	[4]
Lek, B.L.C.,	2018	Treatment of palm oil mill effluent (POME) using chickpea (*Cicer arietinum*) as a natural coagulant and flocculant: Evaluation, process optimization and characterization of chickpea powder.	*Journal of Environmental Chemical Engineering*	84	[40]
Precious Sibiya, N.,	2021	Coagulation treatment of wastewater: kinetics and natural coagulant evaluation.	*Molecules*	81	[35]
Momeni, M.M.,	2018	Using chitosan/CHPATC as coagulant to remove color and turbidity of industrial wastewater: optimization through RSM design.	*Journal of Environmental Management*	79	[36]
Maurya, S.,	2018	Evaluation of plant-based natural coagulants for municipal wastewater treatment.	*Biotech*	74	[34]
Desta, W.M.,	2021	Wastewater treatment using a natural coagulant (*Moringa oleifera* seeds): optimization through response surface methodology.	*Heliyon*	74	[43]
Tawakkoly, B.,	2019	Evaluation of COD and turbidity removal from compost leachate wastewater using *Salvia hispanica* as a natural coagulant.	*Industrial Crops and Products*	74	[44]
Vunain, E.,	2019	Evaluation of coagulating efficiency and water borne pathogens reduction capacity of *Moringa oleifera* seed powder for treatment of domestic wastewater from Zomba, Malawi.	*Journal of Environmental Chemical Engineering*	73	[38]
Subramonian, W.,	2015	An application of response surface methodology for optimizing coagulation process of raw industrial effluent using *Cassia obtusifolia* seed gum together with alum.	*Industrial Crops and Products*	73	[45]
Kusuma, H.S.,	2021	Evaluation of extract of *Ipomoea batatas* leaves as a green coagulant–flocculant for turbid water treatment: parametric modelling and optimization using response surface methodology and artificial neural networks.	*Environmental Technology & Innovation*	69	[46]
Muruganandam, L.,	2017	Treatment of waste water by coagulation and flocculation using biomaterials.	*IOP Conference Series: Materials Science and Engineering*	68	[33]
Yuliastri, I. R.,	2016	The use of *Moringa oleifera* seed powder as coagulant to improve the quality of wastewater and ground water.	*IOP Conference Series: Earth and Environmental Science*	67	[29]
Fard, M.B.,	2021	Utilization of *Alyssum mucilage* as a natural coagulant in oily-saline wastewater treatment.	*Journal of Water Process Engineering*	65	[32]
Januário, E.F.D.,	2021	Performance of a hybrid coagulation/flocculation process followed by modified microfiltration membranes for the removal of solophenyl blue dye.	*Chemical Engineering and Processing: Process Intensification*	61	[30]
Bouchareb, R.,	2020	Combined natural/chemical coagulation and membrane filtration for wood processing wastewater treatment.	*Journal of Water Process Engineering*	57	[47]
Barbosa, A.D.,	2018	Combined use of coagulation (*M. oleifera*) and electrochemical techniques in the treatment of industrial paint wastewater for reuse and/or disposal.	*Water Research*	52	[48]
Cheng, S.Y.,	2020	Sustainable landfill leachate treatment: Optimize use of guar gum as natural coagulant and floc characterization.	*Environmental Research*	52	[31]
Muniz, G.L.,	2020	Performance of natural coagulants obtained from agro-industrial wastes in dairy wastewater treatment using dissolved air flotation.	*Journal of Water Process Engineering*	50	[49]

Among the top publication in natural coagulants research, a significant study is "Performance of Different Coagulants in the Coagulation/Flocculation Process of Textile Wastewater", conducted by Dotto, J. and published in 2019 in the *Journal of Cleaner Production* [2]. This influential paper has accumulated 325 citations. The study presents a comparative analysis of the efficiency of various coagulants, specifically focusing on the natural coagulant derived from Moringa oleifera Lam seeds, extracted using saline solutions of sodium chloride (NaCl) (MO-NaCl) and potassium chloride (KCl) (MO-KCl). The research aims to demonstrate the advantages of using natural coagulants over synthetic alternatives, particularly in terms of cost-effectiveness and environmental sustainability. The methodology involved assessing the performance of two organic coagulants (MO-NaCl and MO-KCl) alongside an inorganic coagulant, aluminum sulfate. The study meticulously evaluated parameters such as apparent color removal, turbidity, COD, and absorbance from TWW samples sourced from an industrial laundry. Using a response surface methodology (RSM), the researchers analyzed the interaction between coagulant concentration and sedimentation time to optimize the C/F process. The results indicated that both Moringa coagulants (MO-NaCl and MO-KCl) achieved remarkable removal efficiencies, with MO-KCl demonstrating the highest performance: 82.2% for apparent color, 83.05% for COD, 78.4% for RP-HE7B, and 89.7% for OP-HER [2].

The second most cited study, "Optimization of Coagulation-Flocculation Process for Treatment of Industrial Textile Wastewater Using Okra (*A. esculentus*) Mucilage as Natural Coagulant", authored by Freitas, T.K.F.S., was published in 2015 in *Industrial Crops and Products* and has received 210 citations [9]. This research investigates the potential of okra mucilage as a natural coagulant in the treatment of TWW, emphasizing its advantages over traditional chemical agents. The study highlights several benefits of using natural coagulants, including biodegradability, low toxicity, minimal residual sludge production, and cost-effectiveness. It specifically focuses on the coagulant activity of okra mucilage (*Abelmoschus esculentus*) and compares its performance with ferric chloride, a commonly used chemical coagulant, in the C/F process. Optimization experiments were conducted using the standard jar test method to evaluate the effects of pH, coagulant dosage, and mucilage dosage on the removal efficiency of COD, turbidity, and color from TWW. The results indicated that a low concentration of okra mucilage (3.20 $mg.L^{-1}$) achieved remarkable removal efficiencies: 93.57% for color, 97.24% for turbidity, and 85.69% for COD, at an optimal pH of 6.0. Notably, the addition of okra mucilage allowed for a significant reduction in the required dosage of ferric chloride, decreasing it by 72.5% (from 320.0 $mg.L^{-1}$ to 88.0 $mg.L^{-1}$), while also enhancing COD removal by 35.74%. The findings demonstrate that okra mucilage is an effective natural coagulant with substantial potential for treating TWW. It not only performed comparably to synthetic coagulants but also provided an environmentally friendly and sustainable alternative [9].

The study titled "The Use of *Moringa Oleifera* Seed as a Natural Coagulant for Wastewater Treatment and Heavy Metals Removal", authored by Shan, T.C., was published in 2017 in *Applied Water Science* and has garnered 151 citations [3]. This research explores the potential of *Moringa oleifera* (MO) seeds as a natural coagulant, emphasizing their effectiveness in treating wastewater and removing heavy metals. The study evaluates the water quality of the Sungai Baluk river before and after treatment with MO seeds. The results indicated a high efficiency of MO seeds in reducing bacterial growth in both wastewater and river samples. Specifically, turbidity was reduced by 85–94%. The study also reported increases in COD and biological oxygen demand (BOD) after treatment, with COD rising from 99.5 $\pm$ 0.71 mg/L to 164.0 $\pm$ 2.83 mg/L and BOD from 48.00 $\pm$ 0.42 mg/L to 76.65 $\pm$ 2.33 mg/L. The removal of heavy metals was a key focus of the research. The study demonstrated that Fe was completely eliminated, while Cu and Cd were removed

by up to 98%. Pb was also reduced by up to 78%. Notably, a 1% concentration of MO seed cake was sufficient to effectively remove heavy metals from all treated water samples [3].

The study titled "Optimized Use of Alum Together with Unmodified Cassia Obtusifolia Seed Gum as a Coagulant Aid in Treatment of Palm Oil Mill Effluent", authored by Shak, K.P.Y., was published in 2015 in *Industrial Crops and Products* and has received 130 citations [39]. This research explores the effectiveness of Cassia obtusifolia seed gum as a coagulant aid in combination with alum for treating high-strength palm oil mill effluent, which can cause severe environmental pollution if discharged untreated. Using response surface methodology, the study optimized the dosages of alum and Cassia obtusifolia seed gum, as well as settling time, to enhance the removal of total suspended solids (TSS) and COD. The combined treatment achieved TSS and COD removals of up to 81.58% and 48.22%, respectively, using optimal conditions of 1.15 g/L of alum, 2.47 g/L of seed gum, and a settling time of 35.16 min. This method required a lower dosage of alum and reduced settling time compared to using Cassia obtusifolia seed gum alone. Characterization of the flocs revealed stable complexes with fibrous networks, enhancing their settling capability [39].

The study titled "Banana Pith as a Natural Coagulant for Polluted River Water", authored by Kakoi, B., was published in 2016 in *Ecological Engineering* and has received 107 citations [41]. This research addresses the contamination of surface water due to poorly managed urban runoff and wastewater systems. The study evaluates the effectiveness of banana pith as a natural polyelectrolyte and coagulant. The biomass was characterized using Fourier transform infrared spectroscopy (FTIR). The banana pith contained 32.3% carbon, 4.21% hydrogen, 1.46% nitrogen, 43.5% oxygen, and 0.86% sulfur. The C/F processes were conducted using various dosages of banana pith and pH values. Remarkably, the treatment achieved turbidity removal rates of up to 98.5%, along with significant reductions in COD, suspended solids, and various heavy metals, including Cu, Cr, Fe, Zn, pb, and Mn, at a dosage of 0.1 kg/m^3 and an initial pH of 4. The study found that the presence of numerous functional groups in banana pith contributed to its effective contaminant removal capabilities. The flocculation process was best described by a second-order kinetic model, with a half-life of 1.16 min and a rate constant of 2.676 m^3/kg/min. Overall, Kakoi's research demonstrates the potential of banana pith as a sustainable alternative to conventional metal coagulants for water treatment, particularly under acidic conditions [41].

The study titled "Mucilaginous Seed of Ocimum Basilicum as a Natural Coagulant for Textile Wastewater Treatment", authored by Shamsnejati, S., was published in *Industrial Crops and Products* in 2015 and has received 102 citations [42]. This research investigates the use of *Ocimum basilicum* (basil) mucilage as a natural coagulant for removing dyes from TWW, specifically targeting the removal of Congo red dye. The study analyzed the effects of three key parameters: pH, coagulant dosage, and dye concentration, on color removal and COD reduction. Among the parameters studied, dye concentration was identified as the most significant factor influencing color removal. The results revealed that a low coagulant dosage of just 1.6 mg/L achieved impressive removal efficiencies: 68.5% for color and 61.6% for COD at a dye concentration of 50 mg/L and a pH of 6.5. The mucilage of O. basilicum was effective not only as a sole coagulant but also in combination with alum, enhancing the treatment of real TWW [42].

The study titled "Capacity of 'Nopal' Pectin as a Dual Coagulant-Flocculant Agent for Heavy Metals Removal", authored by Ibarra-Rodríguez, D., was published in 2017 in the *Chemical Engineering Journal* and has received 85 citations. This research explores the potential of nopal pectin as a coagulant/flocculant for removing heavy metals from synthetic wastewater (SWW) contaminated with metallic ions [4]. Pectins are linear macromolecules characterized by carboxylate and methoxylate groups, which can function as

coagulant/flocculant agents. The study began with the extraction and characterization of nopal pectin using FTIR and nuclear magnetic resonance (NMR), with its molecular weight estimated through viscosimetry. Zeta potential measurements were conducted to assess the surface charge and the ability of nopal pectin to remove various metallic ions, including Ca^{2+}, Cu^{2+}, Zn^{2+}, Cr^{3+}, Ni^{2+}, Pb^{2+}, and Cd^{2+}. The results indicated that an optimal dosage of 0.019 mg/mL of nopal pectin removed up to 99% of all tested metallic ions from the SWW [4].

Table 7 provides a comparison of different natural coagulants utilized in wastewater treatment.

Table 7. Effectiveness of various natural coagulants in wastewater treatment.

Type of Wastewater	Natural Coagulant	Optimal Dosage	Optimum Parameters	Removal Efficiency (%)	Ref.
TWW	MO	MO-KCl: 1.0 g/L	pH 10.9, sediment time: optimized	Color: 82.2%, COD: 83.05%	[2]
TWW	Okra mucilage	3.20 mg/L	pH 6.0	Color: 93.57%, turbidity: 97.24%, COD: 85.69%	[9]
River water and leachate Wastewater	MO	MO: 1%	pH 8.06	Turbidity: 85-94%, Fe: 100%, Cu and Cd: Up to 98%, Pb: up to 78.1%	[3]
POME	*Cassia obtusifolia* gum + alum	Alum: 1.15 g/L, gum: 2.47 g/L	Settling time: 35.16 min	TSS: 81.58%, COD: 48.22%	[39]
Urban runoff	Banana pith	0.1 kg/m^3, initial pH: 4	pH 4.8	Turbidity: up to 98.5%, COD: 54.3%, Zn: 81%, pb: 100%, Mn: 60%, Fe: 92%, Cr: 100%, SS: 96.03%	[41]
Landfill leachate	Guar gum	44.39 mg/L	pH: 8.56, mixing speed: 79.27 rpm	COD: 22.57%	[31]
TWW	*Ocimum basilicum*	1.6 mg/L	pH 6.5	Color: 68.5%, COD: 61.6%	[42]
Synthetic waste	Nopal pectin	0.019 mg/mL	-	Heavy metals: 99%	[4]
POME	Chickpea	2.6 g/L	pH 6.69, mixing speed: 140 rpm	Turbidity: 86%, COD: 56%, TSS: 87%	[40]
Industrial wastewater	Ferromagnetite, alum, eggshells	20 mg/L	30 min	Turbidity, color, TSS: 80%	[35]
Industrial wastewater	Chitosan	3 g/L	pH 3–5.56 for color, settling time: 78.93–105 min, dye concentration: 1000 mg/L removal, initial turbidity: 60 NTU	Color: 76.2%, turbidity: 90.14%	[36]
Municipal wastewater	Banana peel powder, banana stem juice, papaya seed powder, neem leaf powder	0.4 g/L	Room temperature without adjusting initial pH	Turbidity: 59.6% with banana peel powder, TSS: 66.66% with papaya seed powder, COD: 66.67% with banana stem juice.	[34]
Paint wastewater	MO	50 g/L	pH: 6.5	Organic load: 85%	[48]
Wood processing wastewater	MO, various inorganic coagulants	2 g/L	pH: 7	Turbidity: 98.9%, COD: 84.7%, color: 73.7%.	[47]
Acidic and basic wastewater	MO	0.4 g/500 mL	pH 7–9	Turbidity: 99.5% (basic), 98% (acidic), COD: 65.82% (basic), color: 97.7% (basic).	[43]
Landfill leachate	*Salvia hispanica* (chia)	40 g/L	pH 7, contact time: 45 min	Turbidity: 62.4%, COD: 39.76%	[44]
Domestic wastewater	MO	15 g/L	pH 7.1, contact time optimized	Turbidity: 86.5%	[38]
Pulp and paper effluent	*Cassia obtusifolia* gum + alum	Gum: 0.17 g/L, alum: 0.09 g/L	pH 7.2, mixing time: 3.4 min	TSS: 89.6%, COD: 55.4%	[45]
Turbid water	*Ipomoea batatas*	10 g/L	pH 7.0, initial turbidity: 250 NTU, various mixing times (2–10 min) and mixing speed (70–150 rpm)	Turbidity: 96%	[46]
TWW	Potato starch (PS)	–	–	Color: 100%	[30]
Synthesized bilge water	Alyssum mucilage	40.5 mg/L	pH: 7.05, contact time: 34.9 min.	Turbidity: 96.25%, COD: 84.63%, surfactant: 99%.	[32]

Table 7. *Cont.*

Type of Wastewater	Natural Coagulant	Optimal Dosage	Optimum Parameters	Removal Efficiency (%)	Ref.
Tannery effluent	MO, Aloe Vera, cactus	MO: 15 mg/L, cactus: 40 mg/L, Aloe Vera: 5%	pH (MO): 6, pH (Cactus): 7, pH (Aloe Vera): 5	COD: 84%, turbidity: high	[33]
TWW	MO	80–100 mg/L	Varies with initial state	Turbidity: 98.6%	[29]
Dairy wastewater	Okra, passion fruit seeds	Okra: 2 g/L, passion fruit: 1.3 g/L	pH (okra): 9, pH (passion fruit): 5	Turbidity (okra): 91.1%, COD (okra): 48.3% Turbidity (passion fruit): 91.5%, COD (passion fruit): 50.3%	[49]

Table 7 presented reveals the effectiveness of various natural coagulants in treating different types of wastewater. Natural coagulants are effective and sustainable options for wastewater treatment, but their dosage and effectiveness can vary significantly based on the type of wastewater being treated. The effectiveness of various natural coagulants in treating different types of wastewater is influenced by multiple factors, including dosage, pH levels, and the specific contaminants present. Each coagulant exhibits distinct properties that determine the optimal conditions for its use.

MO has been widely studied for its coagulant properties across various wastewater types. For instance, in treated TWW, MO was used at a dosage of 1 g/L, achieving color removal of 82.2% and COD reduction of 83.05% at a pH of 10.9 [2]. This effectiveness can be attributed to the concentration of contaminants present in TWW, which allows for efficient coagulation at lower dosages. Conversely, in paint wastewater, a much higher dosage of 50 g/L was necessary to achieve an 85% reduction in organic load [48]. This variation demonstrates that different wastewater types require specific dosages to effectively neutralize contaminants. Another study applied MO at a 1% concentration in river water and leachate, resulting in turbidity removal rates between 85% and 94% and complete removal of heavy metals such as Fe, Cu, Cd, and pb [3]. In treating tannery effluent, MO at 15 mg/L effectively reduced COD by 84%, maintaining a pH of 6 [33]. Another significant study utilized MO at a dosage of 80–100 mg/L, achieving a remarkable 98.6% turbidity removal [29]. In domestic wastewater, MO at 15 g/L resulted in an 86.5% reduction in turbidity [38]. Finally, when combined with various inorganic coagulants, MO at 2 g/L achieved 98.9% turbidity reduction and 84.7% COD reduction in wood processing wastewater [47]. These findings confirm Moringa's versatility and high performance across diverse wastewater types, with optimal dosages varying based on the specific application.

The pH of the wastewater also plays a crucial role in the effectiveness of coagulants. MO has shown adaptability across varying pH levels, achieving 99.5% turbidity removal in basic conditions and 98% in acidic conditions when applied at a dosage of 0.4 g/500 mL [43]. The charge of contaminants often changes with pH, affecting the coagulant's ability to aggregate particles. Therefore, optimizing pH can significantly enhance the coagulation process, making it essential to tailor the treatment conditions based on the specific wastewater characteristics.

Okra mucilage has demonstrated significant potential as a natural coagulant, particularly in TWW treatment. In one study, okra was applied at an optimal dosage of 3.2 mg/L and a pH of 6, achieving impressive removal efficiencies of 93.57% for color, 97.24% for turbidity, and an 85.69% reduction in COD [9]. This demonstrates okra's effectiveness at low dosages, making it suitable for targeted applications where lower concentrations are preferred. Additionally, when combined with passion fruit seeds, okra at a dosage of 2 g/L achieved a turbidity reduction of 91.1% [49], showcasing its versatility and efficiency.

Cassia obtusifolia gum has been evaluated in several studies, often in combination with other coagulants to enhance treatment efficiency. In one study, a combination of 1.15 g/L of alum and 2.47 g/L of Cassia gum resulted in an 81.58% reduction in TSS and a 48.22% reduction in COD when treating POME [39]. This hybrid approach highlights the potential benefits of using natural coagulants alongside synthetic ones. Another investigation demonstrated that even at lower dosages, such as 0.17 g/L of Cassia gum combined with 0.09 g/L of alum, an impressive 89.6% reduction in TSS and a 55.4% reduction in COD could be achieved [45]. This indicates that Cassia can significantly contribute to wastewater treatment even at minimal concentrations.

Banana pith has proven effective at a dosage of 0.1 kg/m^3 in urban runoff, achieving a turbidity removal of up to 98.5% and a COD reduction of 54.3% [41]. Guar gum, when applied at 44.39 mg/L in landfill leachate, resulted in a 22.57% reduction in COD [31]. Chitosan has also been highlighted for its effectiveness in industrial wastewater treatment, achieving 76.2% color removal and a 90.14% reduction in turbidity at a dosage of 3 g/L [36]. Furthermore, Ocimum basilicum showed efficacy at 1.6 mg/L and a pH of 6.5, resulting in 68.5% color removal and a COD reduction of 61.6% [42]. Nopal pectin demonstrated remarkable effectiveness in synthetic wastewater, achieving 99% removal of heavy metals at a dosage of 0.019 mg/mL [4]. Chickpea, used at 2.6 g/L in POME, resulted in an 86% turbidity removal and a 56% reduction in COD [40].

Other coagulants, such as ferromagnetite, alum, and eggshells, have been used in industrial wastewater treatment at a dosage of 20 mg/L, achieving an 80% removal of turbidity, color, and TSS [35]. Ipomoea batatas, applied at 10 g/L, achieved a 96% reduction in turbidity [46]. Alyssum mucilage in synthesized bilge water at 40.5 mg/L resulted in a 96.25% turbidity removal and an 84.63% reduction in COD [32]. Potato starch achieved complete color removal, although the specific dosage was not provided [30]. Lastly, Salvia hispanica (chia) at 40 g/L in landfill leachate resulted in 62.4% turbidity removal [44].

Overall, the findings underline the necessity of selecting appropriate dosages and treatment conditions tailored to each type of wastewater to optimize treatment outcomes. The versatility of natural coagulants like MO and okra mucilage highlights their potential for effective wastewater management.

3.7. Primary Research Areas of the Application of Natural Coagulants in Wastewater Treatment Research

According to Biberci et al. [50], co-occurrence analysis is crucial for identifying research topics and evaluating the dynamics of research fronts within a specific field. In our study, we employed VOSviewer to analyze the Scopus data we collected, setting a minimum threshold of five occurrences for keywords. Consequently, we retrieved 28 keyword strings from a total of 604 author keywords. Table 8 presents a list of terms that met or exceeded the predetermined threshold established for this study. It is important to emphasize that our focus was on the authors' keywords rather than the indexed keywords. The top 28 keywords are displayed in Table 8 in descending order based on their TLS. The ranking of these keywords was determined through a rigorous scientific methodology that considered factors such as cumulative link strength and the number of connections associated with each keyword.

Table 8 presents the top 28 keywords identified from research related to the application of natural coagulants in wastewater treatment. Key terms such as "Natural Coagulant" and "Coagulation" emphasize the focus on environmentally friendly methods for water purification. The keyword "Turbidity" highlights the importance of measuring water clarity, which is crucial in assessing the effectiveness of treatment processes.

Table 8. Top 28 keywords from the research published on the application of natural coagulant in wastewater treatment.

Keywords	Cluster	TLS	Occurrence
Natural Coagulant	3	141	90
Coagulation	4	102	60
Turbidity	2	58	29
Wastewater Treatment	5	54	33
Wastewater	1	53	27
Moringa Oleifera	6	47	34
Natural Coagulants	2	36	23
Response Surface Methodology	2	36	19
Heavy Metals	1	33	12
Textile Wastewater	3	23	12
Jar Test	2	22	10
Removal	1	22	8
Industrial Wastewater	1	21	8
Coagulant	1	20	15
Coagulation-Flocculation	2	20	14
Removal Efficiency	1	20	7
Water Treatment	3	18	10
Alum	2	17	9
Flocculation	3	17	9
Optimization	2	17	9
Treatment	1	17	6
Turbidity Removal	5	16	12
Adsorption	4	14	8
Congo Red	3	13	8
Dye	4	13	5
Chitosan	5	9	6
Moringa Oleifera Seeds	1	6	5
Coagulation/Flocculation	6	3	5

Particularly noteworthy is the emphasis on "Textile Wastewater" and "Industrial Wastewater", as these types of wastewater are among the most treated using natural coagulants. This underscores the growing need for sustainable solutions in managing effluents that contain high levels of contaminants. The inclusion of "Moringa Oleifera" and "Chitosan" points to specific natural materials recognized for their coagulant properties, promoting eco-friendly alternatives in water treatment. The term "Response Surface Methodology" reflects advanced statistical techniques used to optimize the treatment processes, while "Removal Efficiency" and "Turbidity Removal" focus on the effectiveness of these methods in achieving desired water quality standards. Other keywords, such as "Jar Test" and "Coagulation-Flocculation", indicate practical approaches and methodologies employed in experimental setups.

In this context, Figure 10 displays a network diagram that illustrates the co-occurrence of keywords identified in research articles focused on the application of natural coagulants in wastewater treatment.

The diagram presented in Figure 10 delineates nodes that represent various elements, with their shapes and spatial arrangements signifying the likelihood of co-occurrence among these elements. A thorough examination of the keyword co-occurrence network identifies six clusters, each characterized by a specific color, which correspond to diverse topics within the research area of natural coagulants in wastewater treatment. These colored nodes represent the identified clusters, with each cluster concentrating on a particular discipline pertinent to the application of natural coagulants. The dimensions of the nodes correlate with their frequency of occurrence, while the thickness of the connections between them serves as an indicator of the strength of their interrelations.

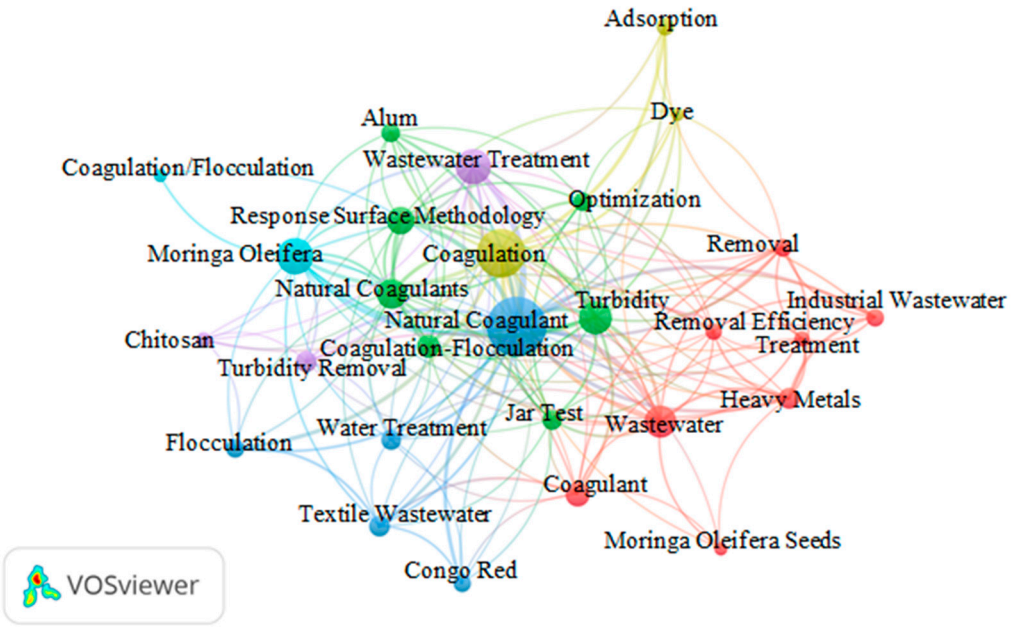

Figure 10. Co-occurrence author keywords related on the application of natural coagulants in wastewater treatment research.

Cluster 1, highlighted in red, comprises eight keywords that are integral to understanding the challenges and solutions associated with heavy metal removal from industrial wastewater. The term "Wastewater" encompasses water that has been adversely affected by various industrial processes, often leading to the release of harmful pollutants. "Heavy Metals" refers to toxic elements such as pb and Cd, which pose significant environmental and health risks due to their persistence and bioaccumulation in ecosystems [8]. The keyword "Removal" signifies the primary objective of wastewater treatment processes, aimed at eliminating these contaminants to safeguard public health and the environment. "Industrial Wastewater" specifies the type of wastewater generated by manufacturing activities, which typically contains a higher concentration of pollutants. The term "Coagulant" denotes substances that facilitate the aggregation of suspended particles, enhancing their removal during treatment. "Removal Efficiency" is a critical metric that assesses the effectiveness of various treatment methods in eliminating contaminants. "Treatment" encompasses a wide range of methodologies employed to purify wastewater, including physical, chemical, and biological processes. Lastly, "Moringa Oleifera Seeds" highlights a specific natural coagulant derived from the Moringa tree, recognized for its ability to effectively reduce heavy metal concentrations in wastewater [43]. This cluster illustrates the importance of innovative approaches, such as the use of natural coagulants, in addressing the pressing issue of heavy metal pollution.

Cluster 2, highlighted in green, features seven keywords that are vital for understanding the coagulation processes involved in wastewater treatment. The term "Turbidity" refers to the cloudiness of water caused by suspended particles, which is a significant concern in both industrial and municipal wastewater. "Natural Coagulants" emphasizes the use of biodegradable and environmentally friendly substances that can effectively replace traditional coagulants like alum [35]. This transition is crucial for reducing the environmental footprint of wastewater treatment [45]. "Response Surface Methodology" represents a statistical approach used to optimize treatment parameters, ensuring that the coagulation process is as efficient as possible [43]. The "Jar Test" is a laboratory procedure commonly employed to determine the optimal dosage of coagulants needed for effective treatment, allowing researchers to simulate real-world conditions [35]. "Coagulation-

Flocculation" describes the combined processes that facilitate the aggregation of particles, which is essential for clarifying water. The use of "Alum", a widely used chemical coagulant, serves as a benchmark for evaluating the performance of natural alternatives [39]. Finally, "Optimization" underscores the importance of refining treatment processes to maximize efficiency and minimize costs. This cluster highlights the significance of both traditional and innovative techniques in enhancing wastewater treatment efficacy.

Cluster 3, highlighted in blue, includes six keywords that focus on the unique challenges associated with treating TWW. "Natural Coagulant" serves as a central term, indicating the use of plant-based substances that can effectively treat TWW. "Textile Wastewater" specifically refers to the effluent produced during fabric manufacturing, which often contains hazardous dyes and chemicals [2]. "Water Treatment" encompasses the various processes applied to purify TWW, aiming to remove harmful substances before discharge into the environment. "Flocculation" is a key process involved in aggregating suspended particles, enhancing their removal during treatment. The term "Congo Red" identifies a specific synthetic dye commonly found in TWW, emphasizing the environmental challenges posed by such contaminants. This cluster illustrates the necessity for specialized treatment approaches tailored to the complexities of textile wastewater, highlighting the potential of natural coagulants as effective solutions.

Cluster 4, highlighted in yellow, consists of three keywords that are essential for understanding the mechanisms of adsorption and dye removal in wastewater treatment. "Coagulation" is a fundamental process that facilitates the separation of suspended solids and contaminants from water, serving as a precursor to adsorption techniques [51]. "Adsorption" refers to the process by which molecules adhere to the surfaces of solids, making it a critical mechanism in the treatment of colored effluents [23]. The keyword "Dye" underscores the focus on removing colorants from wastewater, which is particularly relevant in industries such as textiles and plastics [30]. This cluster illustrates the interplay between coagulation and adsorption techniques, revealing a comprehensive approach to managing dye-laden wastewater effectively.

Cluster 5, highlighted in purple, focuses on three keywords that are crucial for understanding the role of chitosan in wastewater treatment. "Wastewater Treatment" serves as a foundational concept, emphasizing the overall goal of purifying contaminated water. "Turbidity Removal" highlights the specific aim of reducing cloudiness in water, which can be achieved through the application of various coagulants. Lastly, "Chitosan" is a natural polymer derived from chitin, known for its effectiveness in coagulating and clarifying wastewater [36]. This cluster underscores the significance of chitosan as a viable natural coagulant, showcasing its potential to improve water quality while also being environmentally friendly.

Cluster 6, highlighted in orange, centers around two keywords that emphasize the role of Moringa Oleifera in coagulation processes. "Moringa Oleifera" refers to a plant known for its seeds, which are utilized as a natural coagulant in wastewater treatment applications [43]. The term "Coagulation/Flocculation" encapsulates the processes that Moringa oleifera seeds facilitate, demonstrating their potential effectiveness in treating various types of wastewater [3,38,43]. This cluster highlights the emerging interest in utilizing natural resources for sustainable wastewater treatment solutions, illustrating how traditional knowledge and modern scientific approaches can converge to address environmental challenges.

The increasing emphasis on natural coagulants (e.g., Moringa oleifera, chitosan) indicates a significant research trend toward exploring sustainable and eco-friendly alternatives to traditional chemical coagulants like alum. This trend highlights a broader movement in environmental science to reduce reliance on synthetic chemicals and minimize ecological

impact. The presence of keywords related to heavy metals and their removal suggests a concentrated effort in research aimed at addressing industrial wastewater challenges. This includes developing effective treatment methods to mitigate the risks posed by toxic heavy metals, which are prevalent in various industrial effluents. Research is increasingly focused on optimizing treatment processes, as indicated by terms such as RSM and optimization. This trend reflects a commitment to enhancing the efficiency and effectiveness of wastewater treatment methods, ensuring that they are both economically viable and environmentally sound.

The keywords associated with TWW and specific dyes (e.g., Congo red) signify a growing interest in developing targeted treatment solutions for this sector. As textile industries are significant contributors to water pollution, research is directed toward specialized coagulation and adsorption techniques that can effectively address dye-related challenges. The interrelationship between coagulation and adsorption processes is a notable trend, suggesting that researchers are exploring combined methodologies to enhance the removal of contaminants, including dyes and suspended solids. This integrated approach aims to improve overall treatment outcomes.

The emphasis on removal efficiency and metrics for assessing the effectiveness of various treatment methods indicates a trend toward rigorous evaluation of new technologies and techniques. Research is increasingly focused on quantifying the success of natural coagulants in real-world applications, aiming for reproducible and reliable results. The overarching concern with environmental health and the impacts of wastewater pollutants on ecosystems and human health is a critical research direction. Studies are increasingly addressing the long-term consequences of wastewater contamination, driving the need for innovative treatment solutions. These identified trends reflect a dynamic research landscape focused on improving wastewater treatment through sustainable practices, technological advancements, and comprehensive assessments of environmental impact. As awareness of water quality issues grows, the integration of natural coagulants and optimized treatment strategies will likely play a crucial role in future research initiatives.

4. Future Work

As the field of natural coagulants in wastewater treatment continues to evolve due to the exhibited great promise for sustainable wastewater treatment. Recent studies support their efficiency, especially when used in hybrid systems [52–55]. Future work should focus on optimization, scalability, and eco-friendly integration with conventional coagulants for enhanced performance. Several key areas for future work and emerging trends can be identified:

- Expanding research efforts to include a wider range of geographic regions, particularly developing countries, will provide a more comprehensive understanding of the applicability of natural coagulants. Tailoring studies to local conditions will help address unique challenges faced by different regions.
- Future studies should focus on optimizing dosages, pH levels, and other treatment parameters for various wastewater types.
- Exploring the combination of natural coagulants with conventional chemical coagulants or other treatment methods (e.g., adsorption) can lead to improved overall performance. Research should investigate synergistic effects that may enhance contaminant removal efficiency.
- Integrating technologies such as nanotechnology and artificial intelligence can improve treatment processes.

- Investigating the scalability of natural coagulant applications is crucial. Future work should focus on developing cost-effective production methods and exploring industrial applications.
- Incorporating life-cycle assessments in future studies will help evaluate the environmental sustainability of natural coagulants. Research should address not only the effectiveness of these coagulants but also the ecological impacts of their sourcing and processing.

By addressing these future directions and trends, the field of natural coagulants in wastewater treatment can advance significantly, contributing to more sustainable and effective environmental management practices.

5. Conclusions

This bibliometric study provided a comprehensive examination of the research landscape concerning natural coagulants in wastewater treatment, analyzing 268 publications from the past decade. The findings revealed a significant increase in research output, particularly from 2015 onward, with the number of publications rising from just five in 2015 to fifty-one by 2024. This upward trend underscores the growing recognition of natural coagulants as effective solutions for sustainable wastewater management.

The analysis indicated that "environmental science" was the predominant discipline, accounting for 31.3% of the studies, followed by "engineering" and "chemical engineering," which represented 13.6% and 8.5%, respectively. This distribution highlights the interdisciplinary nature of research in this field and the importance of collaboration among various scientific domains. Such collaboration is vital for addressing the complex challenges posed by wastewater treatment and developing comprehensive solutions.

Key contributors included prominent authors like Alazaiza, M.Y.D., and institutions such as the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior in Brazil, which played a crucial role in advancing research efforts. Geographically, Malaysia emerged as a leading contributor, with 60 publications and 1149 citations, followed by India and Brazil, indicating robust scholarly activity in these regions. This geographic diversity illustrates the global commitment to exploring natural coagulants and their applications.

The study identified key natural coagulants, such as Moringa oleifera and chitosan, which are frequently cited for their effectiveness in reducing heavy metal concentrations. The analysis also highlighted effective treatment methodologies, including coagulation/flocculation and adsorption, emphasizing the potential of plant-based materials derived from agricultural by-products. This potential aligns with the increasing demand for sustainable practices in environmental management.

Overall, this study underscores the urgent need for ongoing research to further explore the optimization of treatment processes and the development of novel coagulant formulations. As awareness of water quality issues continues to rise, integrating natural coagulants into wastewater treatment strategies will be essential for promoting environmental sustainability and enhancing public health. This integration will not only contribute to more effective treatment solutions but also support the global transition toward more eco-friendly practices in wastewater management.

Author Contributions: Conceptualization, M.Y.D.A. and M.J.K.B.; methodology, T.M.A.; validation, T.M.A., and M.Y.D.A.; formal analysis D.E.N.; investigation, D.E.N., T.M.A.; writing—original draft preparation, T.M.A.; writing—review and editing M.Y.D.A. and M.J.K.B.; visualization, D.E.N.; supervision, M.J.K.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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