Perspective

The Evolution of Chitosan-Based Adsorbents for Emerging Contaminant Removal: A 2015–2025 Bibliometric Perspective

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Abstract: Emerging contaminants in water bodies, such as pharmaceuticals, dyes, pesticides, endocrine disruptors, and heavy metals, poses serious environmental and health concerns due to their persistence and poor removal by conventional treatment methods. Chitosan-based adsorbents have attracted increasing attention because of their biodegradability, functional versatility, and strong adsorption performance. However, no study has yet provided a systematic bibliometric overview of this research area. This paper presents a bibliometric analysis of 2421 articles published between 2015 and 2025, based on Scopus data and visualised using VOSviewer. The analysis explores publication trends, authors and institutions, influential articles, keyword patterns, and international collaborations. The results show steady growth in both research output and citation impact, with China, India, and Iran leading in productivity. Keyword clustering reveals four major research themes: adsorption mechanisms and modelling, types of target contaminants, behaviour in aqueous systems, and material innovation. Bibliographic coupling and co-authorship networks suggest strong intellectual connections in Asia and a growing global collaboration trend. Despite the maturity of the field, gaps remain in practical applications, regeneration methods, and the integration of predictive modelling. This study offers a comprehensive view of the scientific landscape surrounding chitosan-based adsorbents and highlights future directions for sustainable water treatment research.

Keywords: adsorption; chitosan; emerging contaminants; nanocomposites; bibliometric analysis; water treatment

1. Introduction

Water pollution caused by various emerging contaminants, including pharmaceuticals, antibiotics, heavy metals, dyes, pesticides, endocrine-disrupting compounds, and microplastics, has become a major global concern [1–3]. The term "emerging contaminants" (ECs) refers to synthetic or naturally occurring compounds that are not routinely monitored in the environment but have been increasingly detected in water bodies due to advances in analytical techniques [4]. These pollutants include pharmaceutical residues such as amoxicillin and diclofenac, synthetic dyes like methylene blue and rhodamine B, personal care products, endocrine disruptors such as bisphenol A, as well as pesticides, polycyclic aromatic hydrocarbons (PAHs), and microplastics [2,5] Most of these compounds are persistent, bioaccumulative, and biologically active, making them hazardous even at low concentrations [6,7]. Conventional water treatment technologies, including coagulation, membrane filtration, and advanced oxidation processes, often fail to completely eliminate them or are limited by high operational costs. As a result, adsorption-based approaches have gained increasing attention as cost-effective and efficient alternatives [8–10].

Among the various adsorbents investigated, chitosan-based materials have garnered significant attention due to their biodegradability, non-toxicity, high adsorption capacity, and modifiable functional groups [11,12]. Derived from chitin, a renewable biomass source commonly obtained from seafood waste, chitosan represents a sustainable alternative to conventional adsorbents such as activated carbon, synthetic resins, and silica gels. While the raw material is inexpensive, the processing of chitosan typically involves chemical deacetylation under alkaline conditions, which may increase production costs. As such, chitosan is generally regarded as cost-effective relative to synthetic adsorbents, though it may not be more economical than other low-cost biosorbents like agricultural wastes [13].

Despite extensive research highlighting its excellent adsorption performance at the laboratory scale, the industrial-scale application of chitosan-based adsorption systems remains limited. Current utilization is largely confined to pilot-scale implementations and niche sectors, such as the removal of dyes from textile wastewater and pharmaceutical effluents. Nevertheless, chitosan holds distinct advantages over conventional materials, which often demand high energy inputs or rely on petrochemical feedstocks [14,15]. In contrast, chitosan can be processed under mild conditions and decomposes naturally without producing secondary pollutants. Its amino ($-NH_2$) and hydroxyl (-OH) groups enable strong interactions with pollutants through electrostatic attraction, hydrogen bonding, chelation, and ion exchange mechanisms [16].

Bibliometric analysis offers a systematic approach to mapping publication trends, key contributors, and emerging research themes [17–19]. Unlike conventional review studies that synthesise experimental findings, bibliometric studies provide a macro-level perspective on the intellectual structure and evolution of a research domain. Several bibliometric analyses have been conducted in the broader area of adsorption and water treatment, yet no dedicated bibliometric analysis has systematically examined research trends in chitosan-based adsorbents for emerging contaminant removal. To address this gap, this study conducts a bibliometric analysis of chitosan-based adsorbents for water treatment from 2015 to 2025, using data exclusively from Scopus. VOSviewer is employed to analyse:

- Publication trends over the past decade.
- Key authors, institutions, and countries contributing to this research domain.
- Keyword co-occurrence networks to identify research hotspots and thematic shifts.
- Co-citation and collaboration networks to determine influential studies and research clusters.

The objective of this bibliometric study is to analyze the evolution and impact of chitosan-based adsorbents for the removal of emerging contaminants from 2015 to 2025. This study aims to map the research trends, key contributors, influential publications, and thematic developments in this domain by utilizing bibliometric analysis techniques. By examining publication and citation trends, keyword co-occurrence, and collaboration networks, the study seeks to provide a comprehensive overview of advancements in chitosan-based adsorbents. Additionally, the findings will help identify research gaps, emerging directions, and the global research landscape in sustainable adsorbent technology for environmental remediation.

Although several bibliometric reviews have addressed chitosan applications in water treatment, most have focused on specific subcategories such as hydrogels, metal oxide composites, or photocatalysis. Other studies have broadly discussed chitosan for sustainable development or general wastewater treatment without narrowing the focus to its role as an adsorbent for emerging contaminants. Moreover, none have systematically mapped research progress from 2015 to 2025 using an integrated bibliometric approach focused exclusively on chitosan-based adsorbents. This sustainability-oriented scope aligns with the growing emphasis on eco-friendly materials in environmental remediation. By targeting this specific niche, our study offers a novel and timely synthesis of publication trends, thematic clusters, and collaborative networks, which has not been captured in existing literature.

2. Literature Review

2.1. Chitosan as an Adsorbent for Emerging Contaminant Removal

Chitosan, a natural biopolymer obtained through the deacetylation of chitin derived primarily from marine sources such as shrimp shells, crabs, and fungi, has gained widespread attention as a promising adsorbent for environmental remediation [20–22]. The interest in chitosan is particularly due to its unique properties, including biocompatibility, biodegradability, low cost, abundance, and inherent antimicrobial activity [23,24]. Chitosan's effectiveness in water treatment primarily arises from its high affinity for various contaminants attributed to functional groups like amine ($-NH_2$) and hydroxyl (-OH) (Figure 1), which facilitate selective adsorption [20–22]. These functional groups actively interact with a wide range of pollutants, such as pharmaceuticals, dyes, pesticides, heavy metals, and endocrine-disrupting chemicals, thereby significantly mitigating their detrimental effects on ecosystems and human health. Recent studies have highlighted chitosan's efficacy in the removal of contaminants, including antibiotics and analgesics, which are notoriously challenging to eliminate using conventional methods. For example, chitosan-based composite beads have achieved removal efficiencies as high as 96.8% for copper ions and 99.14% for zinc ions in galvanization wastewater using a hybrid coagulation/flocculation-adsorption process [25]. Similarly, chitosan-activated carbon composites have demonstrated superior adsorption capacities, such as 912.4 mg/g for methylene blue dye, with the material maintaining its effectiveness over multiple regeneration cycles [26]. When compared to conventional adsorbents like activated carbon and polymeric resins, chitosan exhibits comparable or even superior performance, especially when engineered into hybrid materials. For instance, chitosan-based beads incorporated with activated carbon were able to remove over 92% of methylene yellow dye from contaminated water, reaching equilibrium in just 150 min under optimal conditions [27]. In another study, chitosan-derived activated carbon incorporated into a polymeric matrix was shown to efficiently adsorb both cationic and anionic dyes, maintaining over 82% removal efficiency even after five reuse cycles, illustrating its excellent durability and cost-effectiveness [28].

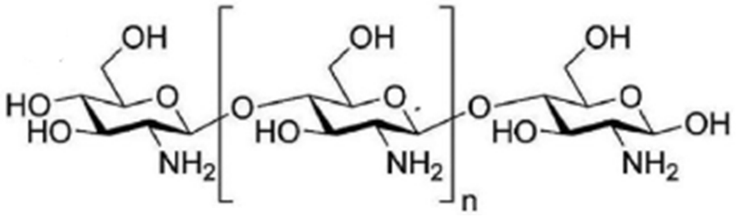

Figure 1. The molecular structure of chitosan [29].

To contextualize the performance of chitosan-based adsorbents, Table 1 presents a summary of commonly used adsorbents and their reported adsorption capacity ranges for emerging contaminants.

Table 1. Typical adsorption capacity ranges of chitosan-based adsorbents as reported in foundational and widely cited studies. Higher capacities may be achieved through advanced modifications.

Adsorbent	Contaminants	Adsorption Capacity Range (mg/g)	Reference
Activated Carbon	Pharmaceuticals (e.g., fluoxetine, acetaminophen)	120–850 mg/g	[30,31]
Biochar	Organic pollutants, dyes, metals	50–500 mg/g	[32,33]
Zeolite	Heavy metals (Zn^{2+}, Pb^{2+}), ammonia	30–200 mg/g	[34]
Chitosan	Metals (Cd^{2+}, Cr^{6+}), pharmaceuticals	20–300 mg/g	[35,36]
Graphene Oxide	Antibiotics, nicotine, doxorubicin	150–670 mg/g	[37,38]
Clay (e.g., montmorillonite, sepiolite)	Metal ions, dyes	20–150 mg/g	[39,40]

Beyond its high adsorption capacity, chitosan is also widely recognized for its environmental benefits. Derived from natural and renewable resources such as crustacean shells, chitosan is biodegradable, non-toxic, and poses minimal environmental risk, which makes it especially suitable for applications aligned with green chemistry and sustainable development principles. This aligns well with the goals of sustainable water management, which emphasize the use of materials that are both effective and environmentally benign. Comprehensive reviews have highlighted the advantages of chitosan-carbon composites, noting their regenerative capabilities, mechanical stability, and broader adsorption spectrum compared to traditional adsorbents [41]. Additionally, the sustainability credentials of chitosan-based materials are enhanced when combined with waste-derived activated carbon or bio-based precursors. These composites not only reduce reliance on synthetic polymers and fossil-derived resins but also contribute to circular economy initiatives by valorizing agricultural and industrial byproducts [42,43].

The evolution of chitosan-based adsorbents spans over four decades, beginning in the early 1980s with fundamental investigations into its capacity to remove metal ions from aqueous media. During this initial phase, chitosan was primarily employed in its raw or deacetylated form, with adsorption attributed to its amine and hydroxyl functionalities [44]. In the 1990s and early 2000s, efforts shifted toward chemical modifications and the fabrication of chitosan beads, membranes, and films to enhance its physicochemical stability, surface area, and selectivity for a broader range of contaminants [45]. The 2010s marked a significant increase in scholarly attention, with nanotechnology enabling the development of composite materials incorporating magnetic nanoparticles, graphene oxide, and metal oxides, thereby achieving higher adsorption capacities and reusability [46,47]. In the most recent decade, chitosan has emerged as a focal material in sustainable water treatment research, particularly for the removal of emerging contaminants such as pharmaceuticals, microplastics, and per- and polyfluoroalkyl substances (PFAS) [48,49]. Green synthesis methods, multifunctional hybrids, and circular economy integration now characterize the forefront of chitosan-based adsorbent development [50]. This historical progression helps contextualize the bibliometric trends observed in the subsequent sections, particularly the sharp rise in publication output over the past 15 years.

2.2. Recent Developments in Modification Techniques

Despite chitosan's significant advantages, its practical application is limited by various drawbacks, including low mechanical strength, low solubility in neutral and alkaline conditions, and instability under acidic environments [51]. To address these limitations, extensive research has been conducted on various modification strategies. These techniques enhance chitosan's structural integrity, adsorption capacity, and applicability in diverse environmental conditions. Physical modifications, including blending, freeze-drying, and bead formation, have been widely employed to improve chitosan's mechanical stability and surface area. For instance, chitosan aerogels crosslinked post-freeze-drying demonstrated a substantial increase in dye adsorption capacity (up to 534.4 mg/g) and mechanical strength when reinforced with graphene oxide [52]. Chemical modifications have also proven effective. Crosslinking with agents such as glutaraldehyde (Figure 2) and epichlorohydrin (Figure 3) stabilizes the polymer under acidic conditions and enhances its adsorption performance for heavy metals like Pb^{2+} and Cu^{2+} [53].

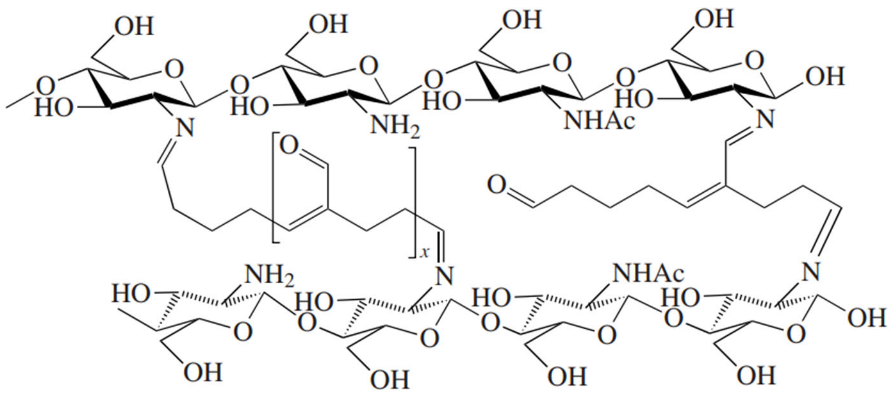

Figure 2. Structures of the products of reaction of chitosan and glutaraldehyde [54].

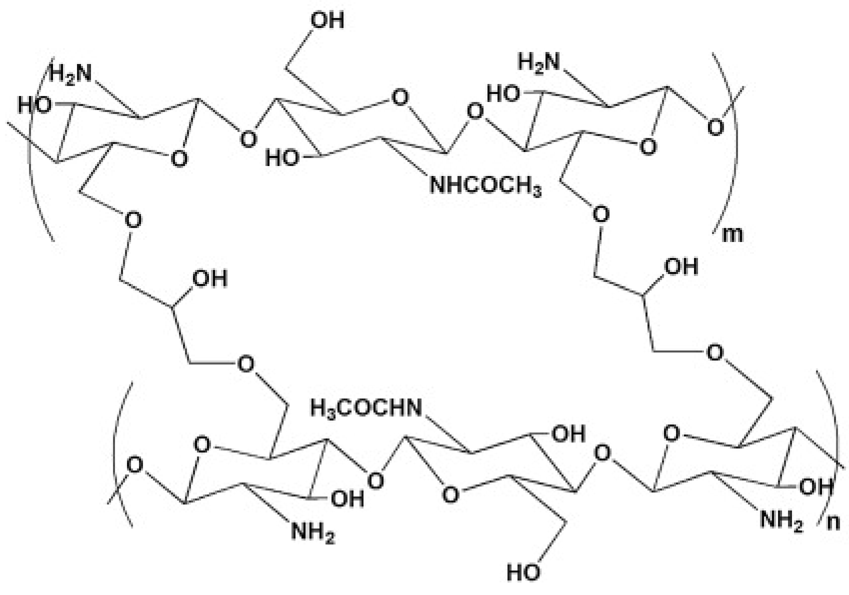

Figure 3. Structures chitosan crosslinked epichlorohydrin [55].

Grafting functional groups or polymers onto chitosan has further expanded its adsorption potential and selectivity. For instance, chitosan grafted with poly(methyl methacrylate) (PMMA) and crosslinked with silica showed high efficiency in Cr(VI) removal while also maintaining biodegradability [56]. Nanocomposite development represents a significant advancement in this field. By incorporating materials such as graphene oxide and silica nanoparticles, researchers have created hybrid chitosan systems with larger surface areas, enhanced pollutant interactions, and faster adsorption kinetics [57,58]. These systems also exhibit higher reusability and are more resilient under diverse pH and temperature conditions. In addition, hydrogels and crosslinked membranes derived from chitosan-carboxymethyl cellulose and graphene oxide have been shown to remove both anionic and cationic dyes efficiently while offering excellent regeneration across multiple adsorption-desorption cycles [59].

2.3. Advancements in Modification Techniques for Enhanced Adsorption Efficiency

Recent advancements in the modification of chitosan have significantly broadened its applicability in environmental remediation, particularly in water and wastewater treatment. While native chitosan possesses attractive features such as biodegradability, abundant active functional groups, and low cost, its practical use is limited by key drawbacks—including poor mechanical strength, insolubility at neutral and alkaline pH, and low selectivity for certain pollutants [57,58]. To address these challenges, recent studies have focused on enhancing chitosan's performance through targeted chemical and physical modifications. Chemical crosslinking remains one of the most effective strategies to improve chitosan's mechanical strength and stability. Crosslinkers such as glutaraldehyde, epichlorohydrin, and genipin have been widely used to create more rigid networks that retain integrity under varying environmental conditions [60]. Complementing these are physical techniques like ionic gelation and freeze-thaw cycling, which enhance hydrogel properties without introducing toxic reagents, making them especially promising for eco-sensitive applications.

The development of chitosan-based nanocomposites has further expanded their environmental relevance. Integration of metal oxides such as Fe_3O_4, ZnO, TiO_2, and CuO has led to the production of hybrid materials with superior adsorption performance, thermal stability, and magnetic separation capabilities. For instance, Cu^{2+}-crosslinked chitosan nanocomposites have demonstrated strong flame-retardant and antibacterial properties in addition to pollutant removal efficiency, extending their utility to multiple environmental domains [61]. Carbon-based nanomaterials such as graphene oxide (GO) and carbon nanotubes have also been increasingly employed in recent studies to improve the adsorptive capacity, surface area, and stability of chitosan composites [62–64] Chitosan-GO hydrogels and membranes have shown excellent results in removing dyes, pharmaceuticals, and heavy metals, often reaching removal efficiencies above 95% under optimized conditions [59,65]. These composites offer improved mechanical strength and regeneration potential, making them suitable for repeated use in dynamic water treatment systems [66]. Nanotechnology has significantly enhanced the kinetic and thermodynamic properties of chitosan-based adsorbents [67]. The nanoscale dispersion of active materials in chitosan matrices increases available surface area and reactive sites, accelerating adsorption rates and boosting capacity. Recent studies report nearly complete removal of pollutants such as lead (Pb^{2+}), chromium (Cr(VI)), and pharmaceutical residues from water using nanostructured chitosan composites [58,68].

2.4. Applications of Chitosan-Based Adsorbents in Water Treatment

Chitosan-based adsorbents have become increasingly prominent in the field of water treatment due to their effectiveness in removing a broad range of emerging contaminants, including pharmaceuticals, endocrine-disrupting chemicals (EDCs), synthetic dyes, and heavy metals. These pollutants, often found in trace concentrations, pose significant environmental and public health risks due to their persistence, bioaccumulation, and toxicity. Recent studies have demonstrated that modifying chitosan with functional nanomaterials greatly enhances its adsorption capacity, specificity, and reusability across diverse contaminant classes. For pharmaceutical contaminants, chitosan-TiO_2 composite membranes have shown outstanding performance, achieving over 98% removal efficiency for antibiotics such as tetracycline and meropenem under visible light irradiation [69]. Similarly, chitosan/polyacrylic acid hydrogels embedded with ZnO-Ti_3C_2TX composites successfully removed up to 90% of norfloxacin, with sustained efficiency over six reuse cycles, highlighting their stability and photocatalytic potential [70].

For endocrine disruptors such as bisphenol A, chitosan-TiO_2 and chitosan-sulfur-TiO_2 composites have also shown high removal efficiencies. A study using a sulfur-doped TiO_2/chitosan/biomass composite achieved 94.6% removal of dyes and 89.7% removal of Cr(VI), suggesting dual applicability for organic and inorganic pollutants [71]. Chitosan composites have been equally effective in dye removal. A study using a chitosan/PVA/TiO_2 composite removed up to 99.9% of methyl orange and 95.76% of congo red via a synergistic mechanism combining adsorption and photocatalysis [72]. Another innovative design, using a thiourea-modified chitosan/ZnS nanocomposite, achieved over 99% removal of multiple dyes (methyl orange, rhodamine B, and methylene blue), underlining the strong dye-binding capacity of chitosan-based photocatalysts [73].

Chitosan composites have also been engineered for heavy metal removal. For example, Fe_3O_4-integrated chitosan-lignosulfonate composites achieved over 90% removal of Cr(VI) and showed high selectivity in mixed metal systems [74]. These high removal efficiencies stem from the interplay of multiple adsorption mechanisms—electrostatic attraction, hydrogen bonding, complexation, ion exchange, and hydrophobic interactions—offering adaptability to a wide range of pollutants. Moreover, recent innovations have explored hybrid systems that combine adsorption and photocatalysis. For example, MXene/ZnS/chitosan-cellulose composites exhibited synergistic effects, achieving up to 100% removal of anionic dyes, driven by enhanced charge transfer and radical generation [75].

2.5. Previous Studies on Bibliometric Analysis of Chitosan-Related Applications

Several bibliometric studies have been conducted to analyse the research trends on chitosan and its applications, particularly in sustainable development and environmental remediation. These studies have provided valuable insights into publication trends, keyword co-occurrence, citation impact, and research collaboration networks. Table 1 shows the previous studies of bibliometic analysis on chitosan-related applications. Hussain [76] explored the progress of chitosan-based hydrogels for water treatment, using Scopus and Web of Science databases. Covering publications from 2000 to 2024, the study examined 235 documents, focusing on publication trends, keyword frequency, citation impact, and top contributors. The findings highlighted a steady increase in research interest, with China and India leading in publications. Lam et. al. [77] conducted a bibliometric analysis of chitosan for sustainable development, analysing 8002 documents from 1976 to 2023 using Scopus. The study focused on document types, subject areas, highly cited publications, and keyword evolution, revealing an increasing emphasis on biodegradable polymers, green chemistry, and water treatment applications.

Ahmad and Chiari [78] studied metal oxide/chitosan composites for organic pollutant removal, analysing keyword co-occurrence and country collaborations. Their findings indicated a growing interest in functionalised chitosan composites for wastewater treatment. Ola et. al. [79] analysed chitosan's role in wastewater treatment, particularly in photocatalyst systems, based on 456 publications from 2001 to 2021. The study highlighted trends in top-cited papers, country-wise contributions, and keyword co-occurrence, showing a strong focus on chitosan's role in photocatalysis for environmental remediation. Yuan et. al. [80] focused on hydrogels in water treatment, covering 1308 publications from 2000 to 2024. The study explored adsorption mechanisms, hydrogel preparation methods, and material performance. The results suggested the need for cost-effective hydrogel materials with enhanced adsorption capabilities.

Despite the significant contributions of previous bibliometric analyses, there remain notable gaps that justify this study. While past research has extensively explored chitosan hydrogels, metal oxide composites, and general sustainable applications, fewer studies have specifically examined chitosan-based adsorbents for emerging contaminants such as pharmaceuticals, endocrine disruptors, and pesticides. Given the rising concern over these pollutants in water sources, a bibliometric study focusing on chitosan's role in their removal is essential to understand the research landscape and identify critical advancements in this area. Additionally, existing bibliometric studies primarily cover research up to 2024, missing recent developments in chitosan-based adsorbents. This study offers a recent and timely overview of research trajectories, emerging keywords, and thematic developments up to early 2024, providing an updated synthesis that reflects trends leading into 2025. To bridge these gaps, this study aims to conduct a comprehensive bibliometric analysis focused on chitosan-based adsorbents for emerging contaminants, analysing Scopus data from 2015 to 2025 to capture the latest research trends and technological advancements. By identifying key research hotspots, dominant contributors, and keyword evolution, this study offers a clearer picture of the field's trajectory and provides a focused bibliometric insight into the role of chitosan-based adsorbents in tackling emerging contaminants, making it a valuable reference for researchers and policymakers.

Compared to the studies summarised in Table 2, the present work fills a clear gap by focusing specifically on chitosan-based adsorbents applied to emerging contaminant removal. While earlier reviews have covered broader scopes such as hydrogels, chitosan-metal oxide composites, or general wastewater treatment, none have centred exclusively on the adsorptive function of chitosan in relation to pollutants like pharmaceuticals, dyes, pesticides, and EDCs. Moreover, this study spans a full decade (2015–2025), capturing the most recent developments in publication trends, thematic shifts, and international research collaborations. This targeted approach provides new insight into an evolving subfield that has not been addressed comprehensively in past bibliometric literature.

Table 2. Previous studies of bibliometic analysis on chitosan-related applications.

Author	Objective	Related Keyword Searched	Data Source and Years Cover	Total Documents Examined	Bibliometric Attributes Examined
[76]	to investigate the progress of chitosan-based hydrogels and their applications associated with sustainable water treatment	Chitosan-based polymer hydrogel Water treatment	Scopus & WOS 2000–2024	235	• Publication by year • Document type • Journal source and publisher • Top citation • Top keywords and occurrence • Top contributing countries • Top authors
[77]	to analyze research trends, global contributions, and emerging applications of chitosan for sustainable development using bibliometric analysis.	Chitosan Sustainable Green Polymer Biodegradable Ecofriendly	Scopus 1976–2023	8002	• Document type • Publication by year • Subject area • Contribution by country • Top source title • Frequently cited publication • Most used keywords • Citation metrics • Country co-authorship • Keyword co-occurrence
[78]	To discuss recent advances of metal oxide/chitosan composites and focus on their application in removing organic pollutants from wastewater	Chitosan’ AND (‘Metal Oxide’ OR ‘ZnO’ OR ‘Fe_2O_3’ OR ‘FeO’ OR ‘magnetic’ OR ‘NiO’ OR ‘CuO’ OR ‘MgO’ OR ‘CrO’ or ‘MnO’ OR ‘CaO’ OR ‘Al_2O_3’ OR ‘AlO’ OR ‘TiO_2’ OR ‘SnO_2’) AND (‘Contaminant*’ OR ‘Pollut*’ OR ‘Wastewater’ OR ‘dye’ OR ‘effluent’) AND NOT ‘heavy metal’	Scopus (years not mentioned)	Not mentioned	• Keyword co-occurrence • Country co-authorship
[79]	to provide a comprehensive bibliometric analysis of chitosan’s role in wastewater treatment, specifically focusing on its evolution in degrading various pollutants within the context of photocatalyst systems.	Chitosan Wastewater	Scopus 2001–2021	456	• Publication by year • Keyword co-occurrence • Subject area • Top journal • Top cited documents • Country
[80]	To analyze the evolution, composition, research hotspots, and trends in hydrogel applications for water treatment from 2000 to 2024	WOS: TS = (“hydrogel” or “aquagel” or “aquogel” or “hydrogels”) and TS = (“water treatment” or “water purify” or “water cleans” or “water remediation” or “water recovery”) CNKI: hydrogel, water treatment, water purification, and water body	Web of Science and CNKI 2000–2024	WOS:1082 CNKI: 226	• Publication by year • Top countries of publication • Top journals • Top cited articles • Top author • Author co-occurrence • Top research organization • Keyword co-occurrence • Number of patents

3. Methodology

Bibliometrics involves collecting, organising, and analysing bibliographic data from scientific publications [81–83]. The study includes fundamental descriptive statistics, including publishing journals, publication year, main author classification [81], and advanced approaches such as document co-citation analysis. In order to conduct a successful literature review, one must engage in an iterative process that includes identifying relevant keywords, conducting a literature search, and performing a thorough analysis to develop a comprehensive bibliography and obtain reliable results [84]. The study aimed to focus on top-tier papers to provide valuable insights into the theoretical perspectives influencing the development of the research field. The study ensured the reliability of the data by utilising the SCOPUS database for collecting data [85–87]. Elsevier's Scopus, renowned for its comprehensive coverage, gathered publications from 2015 to March 2025 for the study.

3.1. Data Search Strategy

The study began with a screening process to identify relevant search terms for article retrieval, initiating the search in the Scopus database, resulting in the assembly of 3447 articles. Subsequently, the query string was refined to focus specifically on the chitosan-based adsorbents for emerging contaminant removal, resulting in a final search string, detailed in Table 3, which yielded 2421 articles for bibliometric analysis. Exclusion criteria outlined in Table 4 were applied during this refinement process. As of March 2025, all articles about glycerol waste utilisation into value-added products from the Scopus database were included in the study. The overall process of data search strategy is as shown in Figure 4.

Table 3. The search string.

Scopus	TITLE-ABS-KEY ((“chitosan”) AND (“adsorption” OR “adsorbent” OR “sorption” OR “biochar”) AND (“emerging contaminants” OR “pharmaceutical wastewater” OR “antibiotics” OR “heavy metals” OR “dyes” OR “pesticides” OR “endocrine disruptors” OR “microplastics”) AND (“water treatment” OR “wastewater treatment” OR “aqueous solution” OR “pollutant removal” OR “contaminant removal”)) AND (LIMIT-TO (DOCTYPE , “ar”)) AND (LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2024) OR LIMIT-TO (PUBYEAR, 2025)) AND (LIMIT-TO (PUBSTAGE, “final”))

Table 4. The selection criterion is searching.

Criterion	Inclusion	Exclusion
Timeline	2015–2025	<2015
Document Type	Article	Review, Conference paper, Book chapter, Erratum, Conference review, Retracted, Short survey, Note, Letter, Data paper
Publication Stage	Final	Article in press

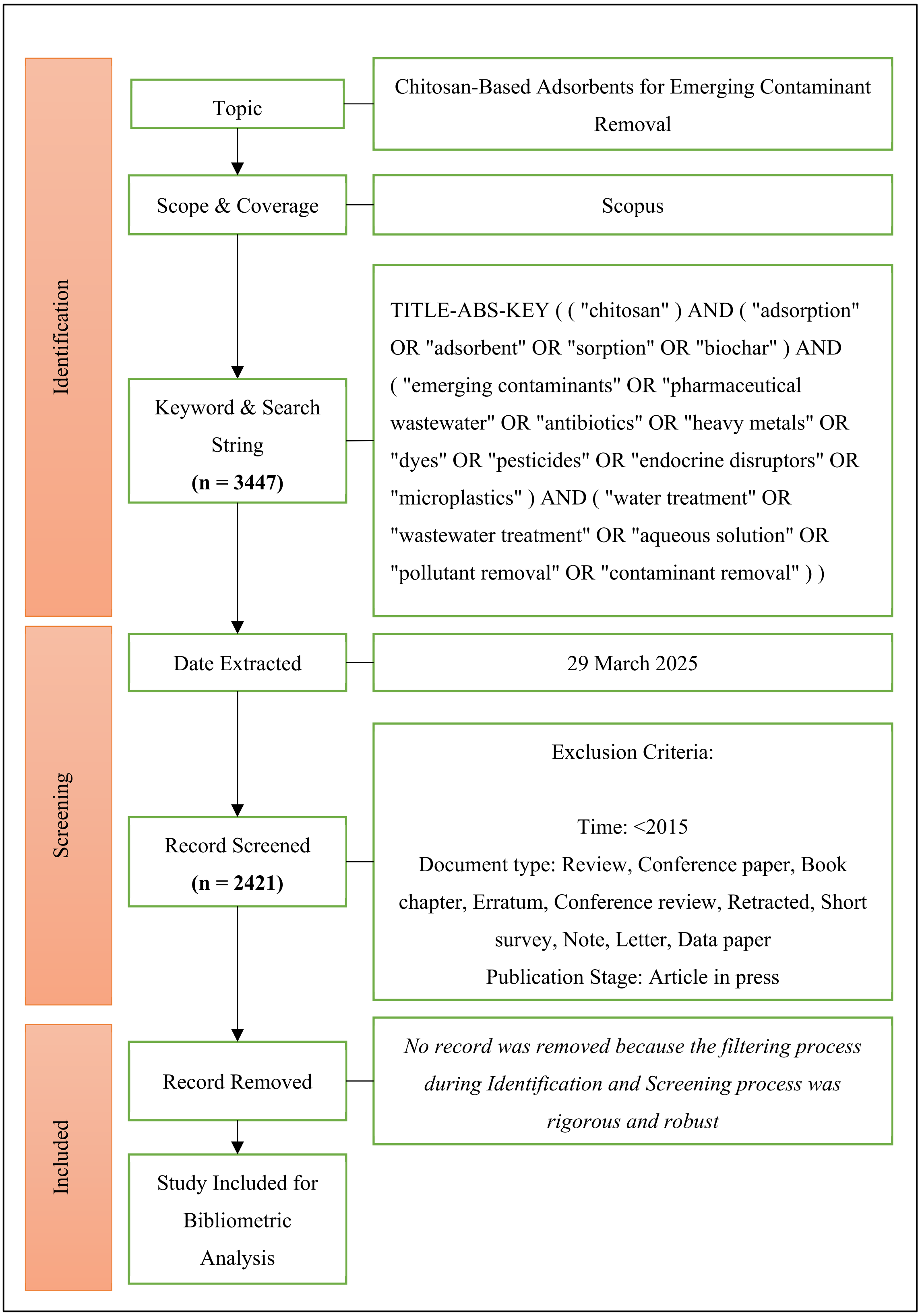

Figure 4. Flow diagram of the searching study [88].

3.2. Analysis of Bibliometric Data

VOSviewer, developed by Nees Jan van Eck and Ludo Waltman at Leiden University, is a widely used bibliometric software known for its intuitive interface and powerful visualisation capabilities. It enables researchers to analyse large datasets through network maps, clustering, and density visualisations [89,90]. This study used VOSviewer version 1.6.19 to analyse Scopus data (2015 –March 2025), processed in PlainText format.

Unlike conventional Multidimensional Scaling (MDS), VOSviewer employs the association strength method to calculate item similarity and positions items in low-dimensional space to reflect their relationships accurately.

The LinLog/modularity normalisation technique was applied to enhance clustering accuracy. VOSviewer's strengths lie in keyword co-occurrence, citation, and co-citation analyses, which help identify research trends, influential publications, and thematic clusters. Co-occurrence analysis reveals how research themes evolve, while citation and co-citation analyses uncover the intellectual structure and connections within the field. Overall, VOSviewer offers a robust, visual approach to exploring the bibliometric landscape of chitosan-based adsorbent research [91,92].

4. Results and Discussion

4.1. Publication Trends in Chitosan Adsorption Research

Figure 5 presents the annual trends of total publications and total citations on chitosan-based adsorbents for emerging contaminant removal from 2015 to 2025. The total number of publications shows a consistent upward trajectory, starting from 113 articles in 2015 and reaching a peak of 372 articles in 2024. This reflects a growing academic interest in the application of chitosan in environmental remediation, particularly in tackling emerging contaminants. Notably, 2025 only shows 111 publications due to incomplete data collection at the time of analysis. In parallel, the total citations increased exponentially from 157 in 2015 to a striking 20,749 in 2024, indicating the increasing impact and recognition of this research domain in the scientific community. The steep rise in citations post-2018, particularly from 2020 onwards, suggests a shift in focus toward sustainable and nature-based solutions in water treatment technologies–likely catalysed by heightened global concerns over environmental pollution and regulatory pressures. Similar upward citation patterns were observed in the bibliometric study by Hussain [76], which attributed the surge in attention to enhanced material design and application efficacy of chitosan-based hydrogels in water treatment. The results in this figure align with findings from Lam [77], who also observed a sharp increase in research output and citations in recent years, indicating that chitosan's role in sustainable development continues to gain relevance.

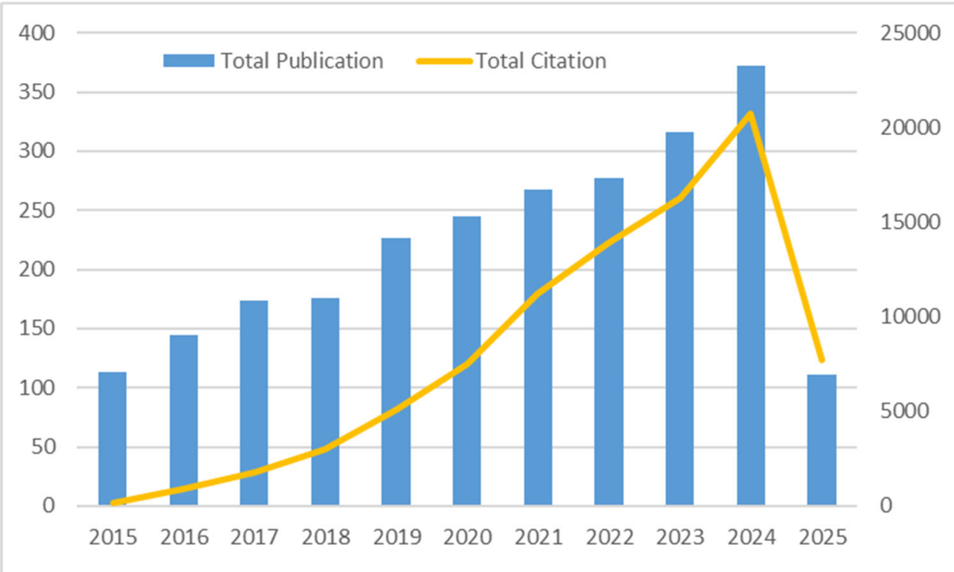

Figure 5. Total publication and citation by year (2015 to 2025).

4.2. Geographical Distribution of Publications

The geographical distribution of scientific output, as presented in Figure 6 and Table 5, reveals that research on chitosan-based adsorbents for emerging contaminant removal is heavily concentrated in Asia and the Middle East. China leads by a substantial margin, contributing 855 publications, followed by India (324) and Iran (270). This dominance reflects both the magnitude of environmental challenges in these countries and their strategic investments in sustainable water treatment research. The concentration of output in these regions suggests that chitosan-based technologies are being actively explored as feasible and low-cost solutions to manage wastewater rich in pharmaceutical residues, dyes, and heavy metals. Malaysia ranks sixth with 114 publications, positioning it as a significant contributor in Southeast Asia. Its presence, alongside countries like Saudi Arabia, Egypt, and Iraq, underlines the expanding footprint of chitosan research in countries facing arid climates and increasing industrial effluent discharge. Notably, while the United States appears in the top ten with 80 publications, its relatively modest count compared to Asian countries may reflect a more targeted focus on high-impact publications rather than research volume alone.

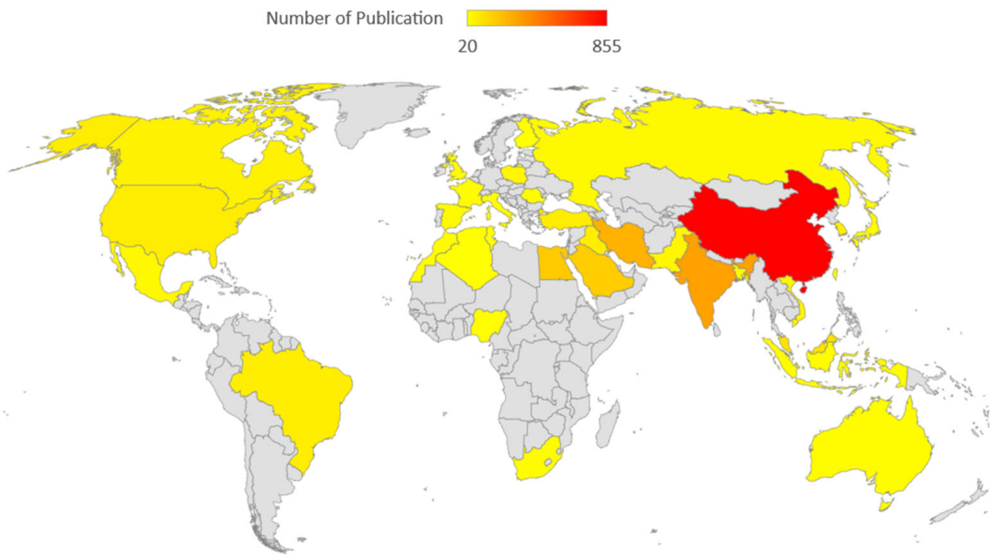

Figure 6. Countries with at least 20 publications.

Table 5. Top 10 countries of publication.

Country	Number of Publication
China	855
India	324
Iran	270
Egypt	194
Saudi Arabia	184
Malaysia	114
United States	80
Turkey	78
Iraq	77
Brazil	76

When analysed in conjunction with institutional contributions (Figure 7), the country-level output can be more deeply contextualised. The Ministry of Education of the People's Republic of China emerges as the most prolific institution with 135 publications, further validating China's leadership in the domain. This is complemented by strong outputs from other Chinese institutions such as the Chinese Academy of Sciences (43 publications), underscoring a robust national-level research infrastructure. From the Middle East, King Saud University (47 publications) and Islamic Azad University (36 publications) represent Saudi Arabia and Iran, respectively. Their positions among the top affiliations highlight not only country-level engagement but also institutional prioritisation of chitosan-based technologies. Similarly, Universiti Teknologi MARA and Universiti Sains Malaysia, with 46 and 26 publications respectively, reinforce Malaysia's active role in advancing research aligned with biomass valorisation and biopolymer applications. The National Research Centre (Egypt) and the University of Anbar (Iraq) also reflect notable institutional productivity within North Africa and the Arab region. Internationally, the University of Saskatchewan (Canada) also appears among the top affiliations, reflecting global interest in chitosan research beyond high-output countries. This suggests that while the volume of research may be concentrated in Asia, there exists a widespread collaborative interest across diverse regions, including North America.

Taken together, these data indicate that chitosan-based adsorbent research is not only regionally driven by water quality challenges but also supported by strong institutional networks and funding mechanisms. The synergy between national strategies and institutional capacities has played a key role in shaping the current landscape, with China clearly dominating both dimensions. This consolidated understanding of country- and institution-level productivity provides a foundational perspective for identifying strategic research partnerships and benchmarking national research agendas in the field of sustainable contaminant removal.

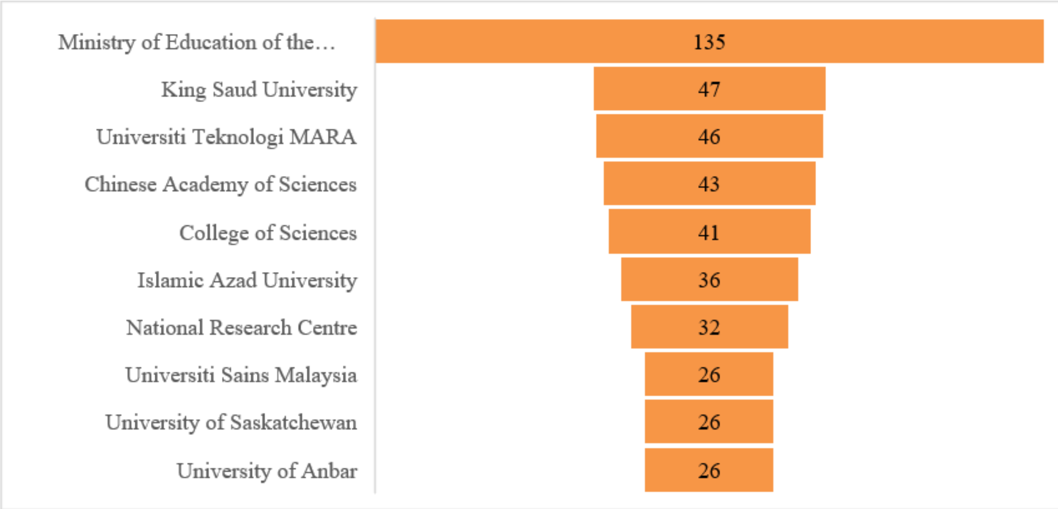

Figure 7. Top 10 contributing affiliations in the field of chitosan-based adsorbents for emerging contaminant removal, based on the total number of publications.

4.3. Top 10 Cited Articles

Table 6 presents the ten most cited articles in the domain of chitosan-based adsorbents for emerging contaminant removal, offering valuable insight into the thematic direction and influential contributions within the field. Citation frequencies range from 297 to 470, reflecting the high impact and relevance of these studies to the global scientific community, particularly in the context of water purification and multifunctional adsorbent design.

The highest cited article, by Tanhaei et al. [93], published in Chemical Engineering Journal, reported the development of a chitosan/Al_2O_3/magnetite nanoparticle composite and its application for Methyl Orange adsorption. The study stands out for its comprehensive approach encompassing kinetic, thermodynamic, and isotherm analyses, which has rendered it a foundational reference for subsequent adsorption studies. This is closely followed by Jamshidifard et al. [94], whose work on the incorporation of UiO-66-NH_2—a zirconium-based metal–organic framework (MOF)—into PAN/chitosan nanofibers for the simultaneous adsorption of Pb(II), Cd(II), and Cr(VI), reflects a broader trend toward the integration of MOFs and chitosan to enhance selectivity and adsorption efficiency. Similarly, the study by Habiba et al. [95], which developed a zeolite-enhanced chitosan/polyvinyl alcohol composite for heavy metal removal, demonstrates the growing importance of nanofibrous membrane systems. These early contributions have catalysed a shift toward hybrid materials that exploit chitosan's functional groups in synergy with inorganic or polymeric supports. The works by Zhao et al. [96] and Li et al. [97] further exemplify this paradigm, where MOF-chitosan composites were successfully immobilised into stable matrices for the removal of tetracycline and other mixed pollutants. These publications, despite being relatively recent, have amassed over 300 citations each—underscoring both the topical relevance of emerging contaminants and the accelerating recognition of chitosan-based hybrid systems in this domain.

A notable feature among the top-cited articles is their shared emphasis on multifunctionality. For example, Chen et al. [98] introduced a magnetically retrievable chitosan composite functionalised with EDTA that demonstrated simultaneous removal of anionic dyes and heavy metals—an approach that directly addresses the complexity of real wastewater matrices. The study by Karthik and Meenakshi [99] also reflects this practical orientation, utilising a polyaniline-grafted chitosan material for heavy metal remediation. These works not only advance adsorbent performance but also embed considerations of cost-effectiveness, scalability, and reusability into their design frameworks.

The journal distribution of these highly cited works reinforces the disciplinary grounding of this research area. The Chemical Engineering Journal emerges as the most prominent outlet, accounting for six of the top ten articles, further affirming its status as a premier venue for high-impact publications in environmental and materials engineering. Other contributing journals such as the Journal of Hazardous Materials, Science of the Total Environment, and the International Journal of Biological Macromolecules reflect the interdisciplinary reach of this field, intersecting chemical engineering, nanotechnology, and environmental science. Collectively, these highly cited articles reveal a clear trajectory in chitosan-based adsorbent research—one that is oriented towards hybrid material systems, broad-spectrum contaminant removal, and practical deployment. The strong citation performance of these works indicates their foundational role in shaping the current and future landscape of advanced adsorbents for environmental applications.

Table 6. Most influential publications based on citation count in the field of chitosan-based adsorbents for emerging contaminant removal.

No.	Title	Source	Year	Cited by	Ref
1	Preparation and characterization of a novel chitosan/Al2O3/magnetite nanoparticles composite adsorbent for kinetic, thermodynamic and isotherm studies of Methyl Orange adsorption	Chemical Engineering Journal	2015	470	[93]
2	Incorporation of UiO-66-NH2 MOF into the PAN/chitosan nanofibers for adsorption and membrane filtration of Pb(II), Cd(II) and Cr(VI) ions from aqueous solutions	Journal of Hazardous Materials	2019	455	[94]
3	Chitosan/(polyvinyl alcohol)/zeolite electrospun composite nanofibrous membrane for adsorption of Cr6+, Fe3+ and Ni2+	Journal of Hazardous Materials	2017	384	[95]
4	Uniform and stable immobilization of metal-organic frameworks into chitosan matrix for enhanced tetracycline removal from water	Chemical Engineering Journal	2020	351	[96]
5	Multifunctional adsorbent based on metal-organic framework modified bacterial cellulose/chitosan composite aerogel for high efficient removal of heavy metal ion and organic pollutant	Chemical Engineering Journal	2020	332	[97]
6	Removal of Pb(II) and Cd(II) ions from aqueous solution using polyaniline grafted chitosan	Chemical Engineering Journal	2015	330	[99]
7	A magnetically recyclable chitosan composite adsorbent functionalized with EDTA for simultaneous capture of anionic dye and heavy metals in complex wastewater	Chemical Engineering Journal	2019	317	[98]
8	Enhancement of ciprofloxacin sorption on chitosan/biochar hydrogel beads	Science of the Total Environment	2018	311	[100]
9	Synthesis and adsorption application of succinyl-grafted chitosan for the simultaneous removal of zinc and cationic dye from binary hazardous mixtures	Chemical Engineering Journal	2015	299	[101]
10	An efficient removal of crystal violet dye from waste water by adsorption onto TLAC/Chitosan composite: A novel low cost adsorbent	International Journal of Biological Macromolecules	2017	297	[102]

4.4. Thematic Clustering of Research Topics

The keyword co-occurrence network reveals four major thematic clusters, each corresponding to distinct research directions within the field of chitosan-based adsorbents for emerging contaminant removal. These clusters, identified through VOSviewer, offer a structured view of the conceptual landscape in the literature. The first cluster is dominated by keywords associated with adsorption mechanisms and modelling frameworks. Core terms such as isotherms, adsorption kinetics, pseudo-second-order model, Freundlich isotherm, and initial concentration indicate that this group encapsulates the analytical foundation of adsorption research. These studies commonly focus on evaluating sorption capacities, fitting kinetic and equilibrium models, and interpreting the thermodynamic behaviour of chitosan-based systems under varying experimental conditions.

The second cluster concentrates on the nature of targeted contaminants and removal performance. Terms such as azo dyes, congo red, heavy metal removal, colouring agent, and antibiotics suggest that this thematic group represents the practical application of chitosan adsorbents to diverse pollutants. The inclusion of antibacterial activity and photocatalysis indicates an emerging interest in multifunctional materials capable of combining adsorption with degradation or disinfection processes. The third cluster reflects keywords related to aqueous environments and physicochemical interactions. Prominent terms include aqueous solution, heavy metals, reaction kinetics, gel, and porosity. This grouping shows that researchers are increasingly considering real-world water matrices and how physicochemical parameters such as solubility, pH, diffusion, and porosity influence adsorption performance and selectivity.

The fourth cluster centres on material synthesis, innovation, and process optimisation. Keywords like hydrogel, nanocomposites, graphene oxide, MOFs, immobilisation, and magnetism demonstrate the emphasis on engineering hybrid chitosan-based materials with enhanced structural and functional characteristics. Additionally, the presence of response surface methodology and Box–Behnken design reflects a rising adoption of statistical design tools to optimise operational parameters and experimental designs, ensuring high-performance pollutant removal under controlled conditions. Together, these thematic clusters demonstrate the evolution of chitosan research into a mature, interdisciplinary domain where mechanistic insights, pollutant-specific applications, environmental context, and advanced material design intersect. The convergence of these clusters underscores the integrative nature of current research efforts and highlights the versatility of chitosan as a platform material in sustainable water treatment.

4.5. Future Research Directions

The bibliometric findings of this study reveal a research field that is both rapidly expanding and diversifying, yet several strategic areas remain underexplored. One of the most notable trends observed is the consistent rise in publications and citations over the past decade, indicating sustained global interest in chitosan-based adsorbents. Despite this growth, emerging pollutants such as pharmaceuticals, endocrine-disrupting chemicals (EDCs), and microplastics—while increasingly studied—still demand more targeted investigations, particularly in terms of adsorption mechanisms and long-term environmental performance.

Several future directions are evident from the keyword clustering and highly cited articles. Firstly, while chitosan composites with materials like graphene oxide, TiO_2, and Fe_3O_4 have demonstrated excellent adsorption capacities, the majority of these studies remain limited to batch-scale experiments. Future research should prioritise the scaling-up of adsorption systems, including the development of continuous-flow column studies, pilot-scale prototypes, and real effluent testing, to bridge the gap between laboratory success and field application. Secondly, although hybrid materials have been well-explored, the regeneration and recyclability of chitosan-based adsorbents remain inconsistent across studies. Future work should establish standardised protocols for regeneration, with particular attention to adsorbent degradation over multiple cycles, desorption efficiency, and secondary waste generation. Exploring non-destructive regeneration methods such as low-energy washing, photocatalytic desorption, or mild chemical treatments would enhance sustainability and applicability.

Thirdly, the dominance of mechanistic and physicochemical studies suggests a maturity in the scientific understanding of adsorption. However, there is a growing opportunity to integrate computational modelling and machine learning approaches for adsorbent design, optimisation, and performance prediction. The incorporation of artificial intelligence (AI)-based methods can accelerate the discovery of novel composite formulations, predict pollutant removal under variable conditions, and guide experimental design through data-driven insights. Furthermore, while keyword co-occurrence shows an active focus on pharmaceuticals and dyes, pesticides and microplastics remain relatively underrepresented. Given the regulatory and environmental urgency surrounding these pollutants, especially in agricultural and urban contexts, future studies should investigate chitosan’s interaction with complex pollutant mixtures, including multi-contaminant systems and competitive adsorption behaviour.

Lastly, the analysis of collaboration patterns indicates that while research on chitosan-based adsorbents is globally distributed, South–South collaborations remain limited compared to North–South linkages. Strengthening regional research networks, particularly among emerging economies that share similar water pollution challenges, would promote technology transfer, enhance contextual relevance, and increase access to locally sourced biomass for chitosan production. While the field has matured significantly, advancing future research will require a deliberate focus on translational science, integrative modelling, circular economy integration, and deeper international partnerships to unlock the full potential of chitosan-based adsorbents in water treatment.

5. **Conclusions**

This bibliometric analysis retrieved 2421 Scopus-indexed articles published between 2015 and 2025 on chitosan-based adsorbents for emerging contaminant removal. The publication trend showed a steady increase, with the highest output recorded in 2024 (372 publications). The top contributing countries were China (855 articles), India (324), and Iran (270), accounting for 49% of the total output. The leading institutions included The Ministry of Education of the People’s Republic of China, King Saud University, and Universiti Teknologi MARA. Keyword co-occurrence analysis identified frequent terms such as *adsorption*, *chitosan*, *wastewater*, and *pharmaceuticals*, reflecting the main research themes. Four major clusters were formed, focusing on (i) adsorption mechanisms and modelling frameworks, (ii) targeted contaminants and removal performance, (iii) aqueous environments and physicochemical interactions, and (iv) material synthesis, innovation, and process optimisation, and. This study not only quantifies the evolution of research output over the past decade but also maps the thematic and institutional landscape of this field. The findings underline a shift from basic synthesis to application-driven studies, though global collaboration remains limited. Future research should prioritise comparative adsorption performance in complex matrices, regeneration efficiency, and real-case environmental validation to advance the practical deployment of chitosan-based adsorbents.

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Declaration of Generative AI and AI Assisted Technologies in the Writing Process: During the preparation of this work, the authors used Grammarly, Quillbot and ChatGPT in order to enhance the clarity, coherence, and grammatical accuracy of the manuscript. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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