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Chitosan-based materials for emerging contaminants removal: Bibliometric analysis, research progress, and directions

Chong Liu^a, Grégorio Crini^{b,*}, Eric Lichtfouse^c, Lee D. Wilson^d, Lorenzo A. Picos-Corrales^e, Paramasivan Balasubramanian^f, Fayong Li^{g,*}

^a Department of Chemical & Materials Engineering, University of Auckland, 1010, New Zealand

^b Chrono-environnement, Université Marie et Louis Pasteur, 25000 Besançon, France

^c State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, 28 Xianning West Rd, Xi'an, Shaanxi 710049, China

^d Department of Chemistry, University of Saskatchewan, 110 Science Place, Room 165 Thorvaldson Bldg., Saskatoon, SK S7N 5C9, Canada

^e Faculty of Engineering Culiacan, Autonomous University of Sinaloa, Culiacan 80013, Sinaloa, Mexico

^f Department of Biotechnology & Medical Engineering, National Institute of Technology Rourkela, 796008, India

^g College of Water Resources and Architectural Engineering, Tarim University, Xinjiang 843300, China

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Chitosan and its derivatives, as natural biopolymers, play a crucial role in various industries such as food, agriculture, paper, medicine, textiles, and biotechnology, as well as in environmental applications, including wastewater treatment. However, a comprehensive bibliometric analysis is lacking to evaluate the current status and research trends in removing contaminants from wastewater through chitosan. This study analyzed 9711 relevant papers published from 1993 to 2024 in the Web of Science database using CiteSpace and VOSviewer software. The findings reveal that Chitosan-based materials—initially investigated for removing metals, dyes, and pesticides—are increasingly explored for tackling emerging pollutants such as pharmaceuticals, personal care products (PPCPs), and *per*- and polyfluoroalkyl substances (PFAS), while research has also expanded to innovative domains including solar-driven water purification scaffolds and advanced composites (e.g., chitosan@graphene oxide, chitosan-based molecularly imprinted polymers, photocatalytic chitosan hybrids, chitosan/clay, and chitosan/metal sulfides). Machine learning methods have been introduced to improve chitosan-based water treatment processes, although progress lags behind that of commercial adsorbents like activated carbon and biochar. Large-scale adoption of chitosan-based technologies requires validation in complex real-world settings, enhancement of cost-effectiveness and regeneration efficiency and mitigation of environmental impacts during chitosan extraction and processing. Future efforts should focus on pilot-scale and field trials, refining chitosan-based materials for niche applications, and developing “smart materials” that respond dynamically to environmental stimuli, ultimately advancing chitosan-based solutions from laboratory-scale demonstrations to impactful, scalable innovations in global water treatment.

1. Introduction

The escalation of population, industrial progress, increased agricultural activity, and heightened waste discharges have exacerbated the challenge of water pollution [1]. Substantial quantities of inorganic contaminants (metal cations and fluorides) and organic contaminants (pesticides, phenols, dyes, volatile aromatics, hydrocarbons, drugs, alkylphenols, and surfactants) are released into aquatic environments, resulting in extensive water pollution that profoundly impacts the survival of numerous aquatic organisms and poses a significant threat to

human health [2]. Hence, it is imperative to develop effective, cost-efficient, and environmentally friendly strategies to eliminate these harmful contaminants from wastewater [14]. Presently, widely employed technologies on an industrial scale encompass physicochemical (precipitation), membrane filtration (nanofiltration, reverse osmosis), ion-exchange, solvent extraction, adsorption and biosorption, and biological techniques (membrane reactor, bioremediation, lagoon treatment, phytoremediation) [15–22]. Among these methods, the adsorption technique remains one of the most extensively employed approaches for treating wastewater containing both organic and

* Corresponding authors.

E-mail addresses: gregorio.crimi@univ-fcomte.fr (G. Crini), lisen8279@163.com (F. Li).

inorganic contaminants, owing to its merits, such as simplicity in design, ease of operation, energy efficiency, and cost-effectiveness [17]. Various adsorbents, including activated carbons, biochar, graphene, carbon nanotubes, zeolites, natural clays, metal oxides, and polysaccharides, have found widespread application in removing contaminants from wastewater [23–26]. Among them, the most used in industry are commercial activated carbons (CAC) due to their high efficiency toward an extensive range of contaminants. However, active carbon technology also presents several disadvantages. CAC is quite expensive, and the higher the quality, the greater the cost. In general, using CAC-based materials are often unjustified for most pollution control applications and environmental purposes. There is also the drawback of their rapid situation and, thus, their regeneration. This regeneration step is costly, not straightforward, and results in carbon loss.

The opportunity now exists to consider other solid materials for water and wastewater treatment applications. Indeed, in the last two decades, various studies have been carried out to replace CAC with other adsorbent materials, called non-conventional materials, such as biomass, natural materials (bentonite and alunite), agricultural wastes, residue wastes from forest industries (sawdust and bark), industrial by-products, and biopolymers [27]. The increasing demand for biopolymers and oligomers with low-cost, high porosity and surface area, high adsorption capacities, and easy regeneration, such as cellulose, alginate, starch, cyclodextrin, chitin, and chitosan, has attracted much attention [26,28,29]. Among them, chitosan is considered one of the most promising materials for water purification due to its high affinity for different water contaminants [17,26]. As shown in Fig. 1, chitosan is derived from the partial deacetylation of chitin, the second most abundant natural polymer after cellulose. Chitin is found in shrimp shells, carbohydrate shells, and some fungi [15,26,30]. Chitosan and its derivatives have been used in various applications in food, personal care, agriculture, medicine, textiles, biology, chemistry, and the environment [31]. Numerous studies have shown that chitosan-based materials can also act as adsorbents and as a natural flocculant to remove dyes and metal cations from wastewater [29,31–36]. In addition, chitosan-based materials can be used as a support matrix for photocatalysts for the synergistic degradation of organic contaminants through adsorption/photocatalysis [25,37–39].

When searching the “SCOPUS” database with “chitosan” and “water treatment” as subjects, a total of 28 articles were classified as review articles from 2022 to 2024 (as of 10 January 2025), with these reviews systematically addressing the use of chitosan-based materials for the removal of wastewater contaminants [Text S1 (Supporting information)]. Table 1 provides a concise summary of the selected reviews. However, these existing reviews primarily focus on process optimization and technological advancements, emphasizing general chemical properties and broad environmental applications. Yet, they fall short of offering a comprehensive perspective on the research landscape and emerging trends. This gap limits our ability to derive novel insights from

Table 1

Synopsis of previous reviews of chitosan-based materials for wastewater treatment in 2022–2024 (selected works).

Review title	Comment	CA*	Date	Ref.
Biosorption of wastewater pollutants by chitosan-based porous carbons: A sustainable approach for advanced wastewater treatment	This review introduces the adsorption performance of chitosan-based porous carbon biosorbents for the removal of toxic pollutants (metal ions and dyes) from polluted water.	Azry Borhan	2024	[47]
Chitosan-based polysaccharides for effective synthetic dye adsorption	This review illustrates the potential of chitosan and its derivatives as effective adsorbents for dye removal in wastewater treatment processes.	Linda Hevira	2024	[48]
A review on chitosan/metal oxide nanocomposites for applications in environmental remediation	This review presents chitosan/metal oxide nanocomposites with potential and practical applications in environmental remediation and monitoring.	Hua-Yue Zhu	2024	[49]
A review on the progress of magnetic chitosan-based materials in water purification and solid-phase extraction of contaminants	This review focuses on the application of magnetic chitosan-based materials for the efficient removal and magnetic solid-phase extraction of contaminants such as heavy metal ions, organic dyes, antibiotics, and other contaminants.	Hua-Yue Zhu	2024	[50]
The use of chitosan-based composites for environmental remediation: A review	This review discusses the present design and preparation methods of chitosan and its composites, along with their applications in removing different pollutants through adsorption and photocatalytic processes.	Mahmoud Adel Ahmed	2023	[25]
A Review on Recent Advances in Polymer-Assisted Green and Sustainable Technology for Remediation of Pharmaceuticals from Water and Wastewater	This review summarizes the occurrence of commonly used pharmaceuticals in reservoirs and their removal through adsorption and photodegradation using environmentally friendly polymer-based composites.	Mohammad Tahir Aminzai	2023	[51]
Chitosan-based beads as sustainable adsorbents for wastewater remediation: a review	This article reviews chitosan-based beads for wastewater treatment, focusing on adsorption mechanisms, contaminant removal, functionalization, metal-organic frameworks, magnetic beads, imprinted and copolymeric beads, and regeneration.	Mahendra Chinthala	2023	[52]

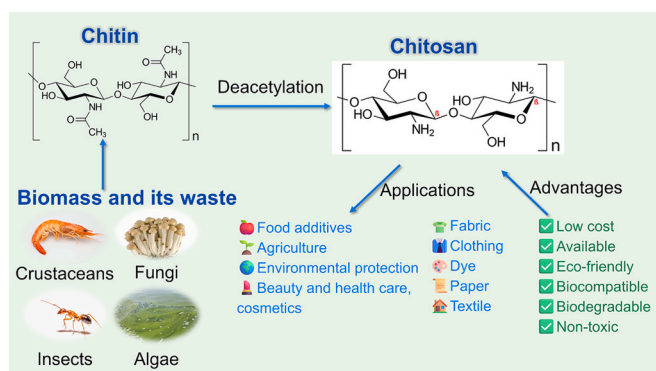


Fig. 1. Preparation, advantages, and applications of chitosan.

(continued on next page)

Table 1 (continued)

Review title	Comment	CA*	Date	Ref.
Recent advances in chitosan-based nanocomposites for dye removal: a review	This article discusses recent advances in chitosan and its derivatives as adsorbents or photocatalytic materials for environmental remediation of toxic dyes.	K. Pathakoti	2023	[53]
Chitosan as adsorbent for removal of some organic dyes: a review	This paper primarily discusses the current advancements of chitosan as a substance used to remove specific organic colors by adsorption.	Z. Saigl	2023	[54]
A review on heavy metal biosorption utilizing modified chitosan	This paper specifically examines the notion of biosorption, including its various forms, architectures, and features. It also explores the application of modified chitosan, as well as mixes and composites that have undergone physical and chemical modifications, for the purpose of removing heavy metals from water.	Sarita Joshi	2023	[55]
Advanced technologies in water treatment: Chitosan and its modifications as effective agents in the adsorption of contaminants	This review discusses the applications of chitosan and its modified materials in water treatment, highlighting their adsorption capabilities for removing contaminants such as heavy metals, dyes, and emerging pollutants. It analyzes the structural properties of chitosan, various modification methods, and its potential for environmental sustainability and wastewater management in the post-pandemic era.	Janaína Oliveira Gonçalves	2024	[56]
This work	Through bibliometric analysis, this study comprehensively reviews and synthesizes research on chitosan-based materials for pollutant removal in water and wastewater, providing valuable insights into the future large-scale application of chitosan-based materials.	G. Crini	–	–

CA*: Corresponding author.

a developmental standpoint. Furthermore, the current literature lacks in-depth reviews on some burgeoning directions in the application of chitosan for water treatment. Specifically, there is a need for a comprehensive review addressing the removal of emerging contaminants using chitosan-based materials, the integration of chitosan in solar-driven water evaporation, and the utilization of machine learning (ML) to advance research on chitosan and its related materials. Bibliometrics integrates mathematical and statistical methodologies, providing a comprehensive analysis to describe, evaluate, and predict the current status and developmental trends of a research field [40–42]. It combines the characteristics of literature, identifies future trends, and offers novel perspectives for subsequent researchers. Recently, bibliometric analyses have been applied to wastewater treatment research, such as emerging contaminants in wastewater treatment [43], adsorbents for adsorption-based techniques [44], virus removal methodologies [45], and ozone technology applications [46]. In order to fill the gap in previous studies, this bibliometric analysis aims to:

- (1) analyze the annual publication trends of water treatment with chitosan-based materials from 1993 to 2024;
- (2) reveal the leading journals, authors, and countries;
- (3) analyze the keywords and essential literature to summarise the research hotspots in the field;
- (4) outline the main current challenges and future trends.

Overall, this bibliometric review analysis provides many researchers with quantitative and qualitative scientific insights that can provide guidance for future research on wastewater treatment with chitosan-based materials.

2. Methodology

Considering the comprehensiveness and authority of data, retrieval for this study emanated from a search within the Web of Science (WOS) core database. The search terms were TS = (chitosan OR poliglusam OR deacetylchitin OR poly-(D)glucosamine OR chitopearl OR chitopharm OR flonac OR kytex) AND (sorption OR removal). Citation topics *meso* = (2.90 Water Treatment) was set, the period was from 1 January 1993 to 31 December 2024, the type of literature was articles and reviews, and a total of 9711 papers were included. Utilizing bibliometric tools such as Citespace (version 6.1.R6), VOSviewer (version 1.6.19), and Scimago Graphica (version 1.0.36), bibliometric and visualization analyses were conducted. This study selected CiteSpace and VOSviewer due to their complementary functionalities in bibliometric analysis. CiteSpace excels in identifying research hotspots, co-citation networks, and trend evolution, while VOSviewer is highly effective in visualizing large-scale co-occurrence networks. Both tools are widely used in scientometric studies and offer robust data processing capabilities, making them well-suited for our research. In CiteSpace, the time frame of this study was set to 1993–01–2024–12, with a “Year per Slice” parameter of 3, while other settings remained at default values. Fig. 2 displays the flowchart illustrating the search and analysis process.

3. Results and discussion

This article conducted a bibliometric analysis according to Fig. 2, and the results and discussion are as shown in Text S2 (Supporting information).

4. Current research progress and research hot spots

By analyzing keywords, topics, and cited documents in recent years, research hot spots and trends in this field can be determined to a certain extent. In CiteSpace, the year range is configured from 2018 to 2024 with a time interval of 1 year. This study conducted burstness analysis and cluster analysis on the topics, keywords, and cited documents of the

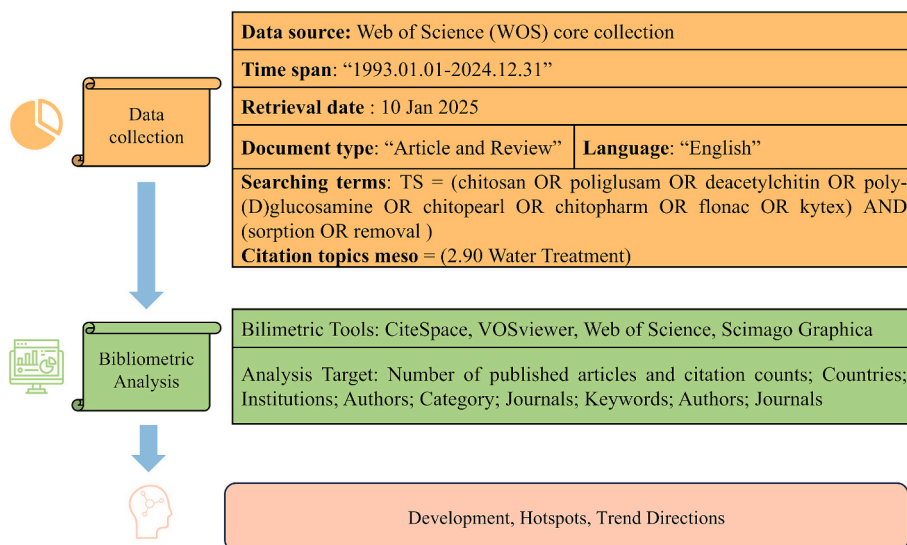


Fig. 2. A scheme of document collection and bibliometric analysis.

retrieved documents. This analysis provides a comprehensive overview of recent advances, research highlights, and future directions on using chitosan materials to remove contaminants from aqueous environments.

4.1. Chitosan-based materials remove emerging contaminants from water

The use of chitosan-based materials to generate metal cations, dyes, and pesticides in aqueous environments has been widely discussed (Supplemental Materials). In addition, Table 1 shows that the previous review of chitosan-based materials for removing traditional pollutants has been explained, introduced, and discussed in great detail. Indeed, a comprehensive review on the removal of emerging contaminants by chitosan-based materials is currently lacking in the literature. Therefore, this study focuses on discussing the removal of emerging contaminants by chitosan-based materials. Chitosan-based materials have garnered substantial attention and scholarly inquiry for their efficacy in eliminating emerging contaminants from aqueous environments. The spectrum of these emerging contaminants encompasses, but is not confined to, environmental endocrine-disrupting chemicals, pharmaceuticals and personal care products (PPCPs), nanomaterials, poly- and perfluoroalkyl substances (PFAS), and antibiotic resistance genes [57–60]. Compared with the research on removing emerging organic matter using other materials (such as activated carbons, biochars, and zeolites), the related research on chitosan is still insufficient. With increasing research attention, this study explores the application of chitosan-based materials in removing PPCPs and PFAS from wastewater.

4.1.1. Removing PFAS from wastewater

The environmental challenges posed by PFAS have garnered significant attention from researchers due to the ubiquitous presence of PFAS in various environmental matrices (water, atmosphere, soil), as well as in animals and humans [61]. It has been reported that the number of PFAS types exceeds 9000, with well-known substances like perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) incorporated into the *Stockholm Convention* [62]. Among the diverse treatment methodologies employed for PFAS removal from wastewater and environmental matrices, adsorption stands out for its simplicity in operation, high efficacy, and energy efficiency [63]. CAC and organic resins are the predominant adsorbent materials that are often suggested for efficiently removing PFAS from wastewater [63]. Moreover, CAC has been reported as the most widely used method for commercial-scale removal of PFAS from water and wastewater [64,65]. However, their application is limited by low removal efficiency for short-chain PFAS

compounds (4–7 perfluorocarbons), competitive adsorption of other organic compounds, and the non-renewable nature of the adsorbents [65–67]. The use of organic resins for treating PFAS in wastewater also faces similar challenges [64,65]. Researchers are increasingly interested in developing alternative adsorbents derived from abundant renewable natural resources or other low-cost sources to address the aforementioned issues.

Some studies have elucidated that, among the polysaccharide-based adsorbents investigated thus far, chitosan-based adsorbents exhibit superior adsorption capacity for PFAS [65,68,69]. This is attributed to the active functional groups of chitosan, such as $-NH_2$ and $-OH$, which can be chemically modified through crosslinking, functionalization, and other approaches to enhance their adsorption efficiency [68,69]. The possible mechanisms for the adsorption of PFAS by chitosan-based materials include electrostatic interactions, hydrophobic effects, and self-aggregation (formation of micelles or hemimicelles), as illustrated in Fig. 3. Though some of these chitosan-based adsorbents have yielded encouraging results, to date, only a limited number of studies in the literature have considered the removal of PFAS by chitosan-based adsorbents in batch systems (Table 2). As shown in Table 2, the reported adsorption capacities vary considerably among different chitosan-based adsorbents. These differences can be attributed to multiple factors, including the type of crosslinker employed (e.g., glutaraldehyde, epichlorohydrin), the specific PFAS targeted (long-chain vs. short-chain), the solution pH and ionic strength, as well as the overall pore structure and surface chemistry of the modified chitosan. The reasons mainly stem from two aspects: (1) pristine chitosan has low solubility under neutral or acidic pH conditions; (2) pristine chitosan exhibits slow adsorption kinetics due to its compact non-porous structure, which limits its application for PFAS removal. Therefore, to improve the stability of chitosan-based materials in aqueous solutions, surface modifications (e.g., grafting, crosslinking, blending, and coating) are necessary using different cross-linkers (e.g., glutaraldehyde and epichlorohydrin). These modifications not only help overcome the poor solubility and limited mass transfer of pristine chitosan but also give rise to more favourable surface properties, thereby accounting for the higher adsorption capacities reported in the literature for some chitosan-based adsorbents. This is essential for improving the adsorption performance of chitosan-based materials for PFAS removal.

In addition to surface modification of chitosan-based materials, another important factor influencing the adsorption of PFAS by chitosan-based materials is the pH value of the solution. This contributes to the fact that the $-NH_2$ functional group of protonated chitosan in

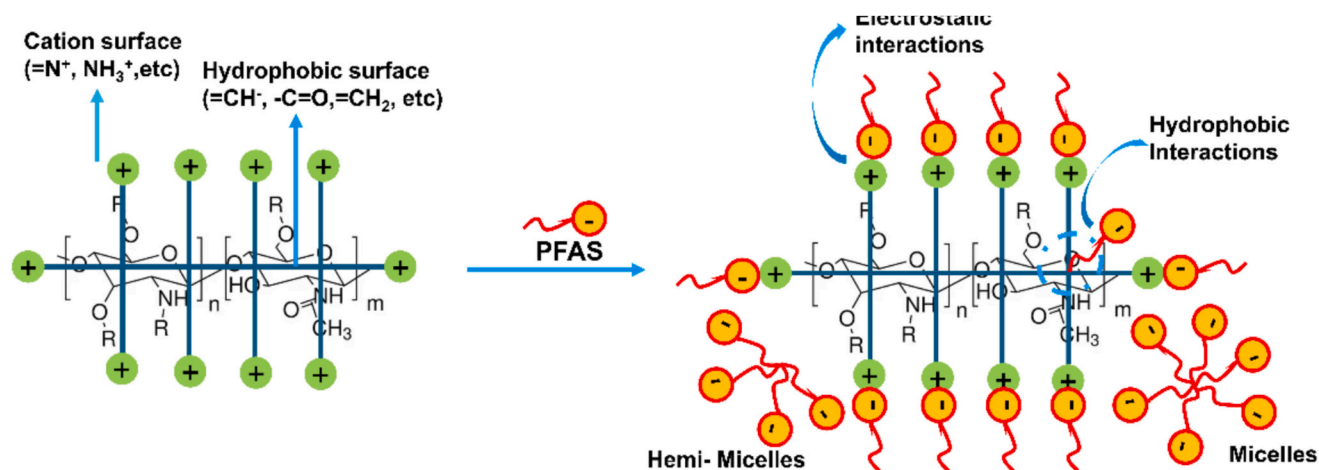


Fig. 3. The mechanisms for the adsorption of PFAS by chitosan-based materials. Modified from [69].

Table 2

A comparison of adsorption capacities for PFAS of chitosan-based materials.

Adsorbent Type	Cross-linkers	Target PFAS	Adsorption Capacity		Regeneration		Ref.
			Suitable pH value	Q_{\max} (mg/g)	Desorption eluents	Maximum desorption efficiency	
Chitosan beads	Epichlorohydrin	PFOS	pH = 3.0	2750.87	-	-	[72]
Chitosan-based MIP	Epichlorohydrin	PFOS	pH = 5.0	1450.46	NaOH/acetone (9:1 v:v)	-	[73]
Chitosan-ethylene glycol hydrogel	-	PFOA	pH = 2.0	1275.90	-	-	[74]
Chitosan / β -cyclodextrin sorbent	Glutaraldehyde	PFBS	pH = 2.0	135.70	Methanol	96.5 %	[75]
Magnetic chitosan beads	Glutaraldehyde	PFOA, PFOS	pH = 3.0	PHOA = 16.07 PHOA = 21.64	Ethanol	-	[76]
Chitosan/F-COF	Sodium tripolyphosphate	PFOA, PFOS, GenX	-	PFOS = 8307.10 PFOA = 6177.10 GenX = 4603.30	-	-	[77]
Chitosan/CAC	NaOH	PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA	pH = 5.0	-	-	-	[78]
Alginate / chitosan / polyethyleneimine	Glutaraldehyde	9 PFAAs, GenX, and 2 PFAS precursors	-	PFAS = 12,133.00	-	-	[68,79]
Chitosan beads	Diepoxyoctane	GenX	pH = 2.0	825.90	NaCl /methanol (3:7 v:v)	84.3 %	[80]
Chitosan beads	Epichlorohydrin	PFOA,PFOS,PFBA,PFBS	pH = 6.0	PFOA = 230.03 PFOS = 250.08 PFBA = 305.79 PFBS = 230.85	-	-	[71]

acidic solution media possesses the capability to attract the anionic headgroups (COO^- and SO_3^-) of PFAS through electrostatic interactions [63,68,69]. Besides, previous research has demonstrated that the adsorption of PFAS (with pK_a values of 2.80 and - 3.27 for PFOA and PFOS, respectively) by chitosan beads attains its zenith when the solution pH is calibrated to 2.0–3.0, a finding corroborated in numerous reviews [69,70]. Nevertheless, in contrast to prior observations, a recent study describes that chitosan beads exhibit heightened efficiency in removing PFAS under acidic conditions, reaching its pinnacle at pH = 6.0 [71]. The rationale lies in that, at a pH value around 6.0, PFAS undergo deprotonation, transitioning gradually into a fully anionic state, thereby facilitating more efficient interaction with protonated chitosan materials. Furthermore, given the higher hydrophobicity of long-chain PFAS compared to their short-chain counterparts, the adsorption of short-chain PFAS is more susceptible to pH variations than long-chain PFAS [71]. While some reviews have highlighted that most experimental studies report significant PFAS adsorption by chitosan at pH levels of 2.0–3.0, it is crucial to recognize that maintaining such low pH values is impractical in real-world wastewater treatment

applications. Therefore, future research should focus on optimizing this treatment method under conditions closer to neutral pH.

Based on the information provided in Table 2, this study found some interesting modification methods that are worth mentioning. He et al. have synthesized chitosan/F-COF adsorbent, as illustrated in Fig. 4a [77]. The chitosan/F-COF exhibits exceptional adsorption properties for PFOS and PFOA, with an outstanding maximum adsorption capacity (Q_{\max}) reaching 8307.10 mg/g and 6177.10 mg/g, respectively, which significantly surpassing traditional adsorbents such as granular activated carbon and hierarchically microporous biochar. Nevertheless, the chitosan/F-COF adsorbent has two main drawbacks: (1) the high cost associated with COF and (2) the inability to undergo adsorption regeneration. Another study synthesized alginate, chitosan, and polyethyleneimine-functionalized fibres/aerogels, which were used to adsorb a mixture of 12 types of PFAS [68]. These materials exhibited a maximum adsorption capacity of 12,133 mg/g, the highest reported in this study. Subsequent research by the same group further improved the adsorption efficiency for short-chain and low-concentration PFAS through density functional theory (DFT) modelling [79].

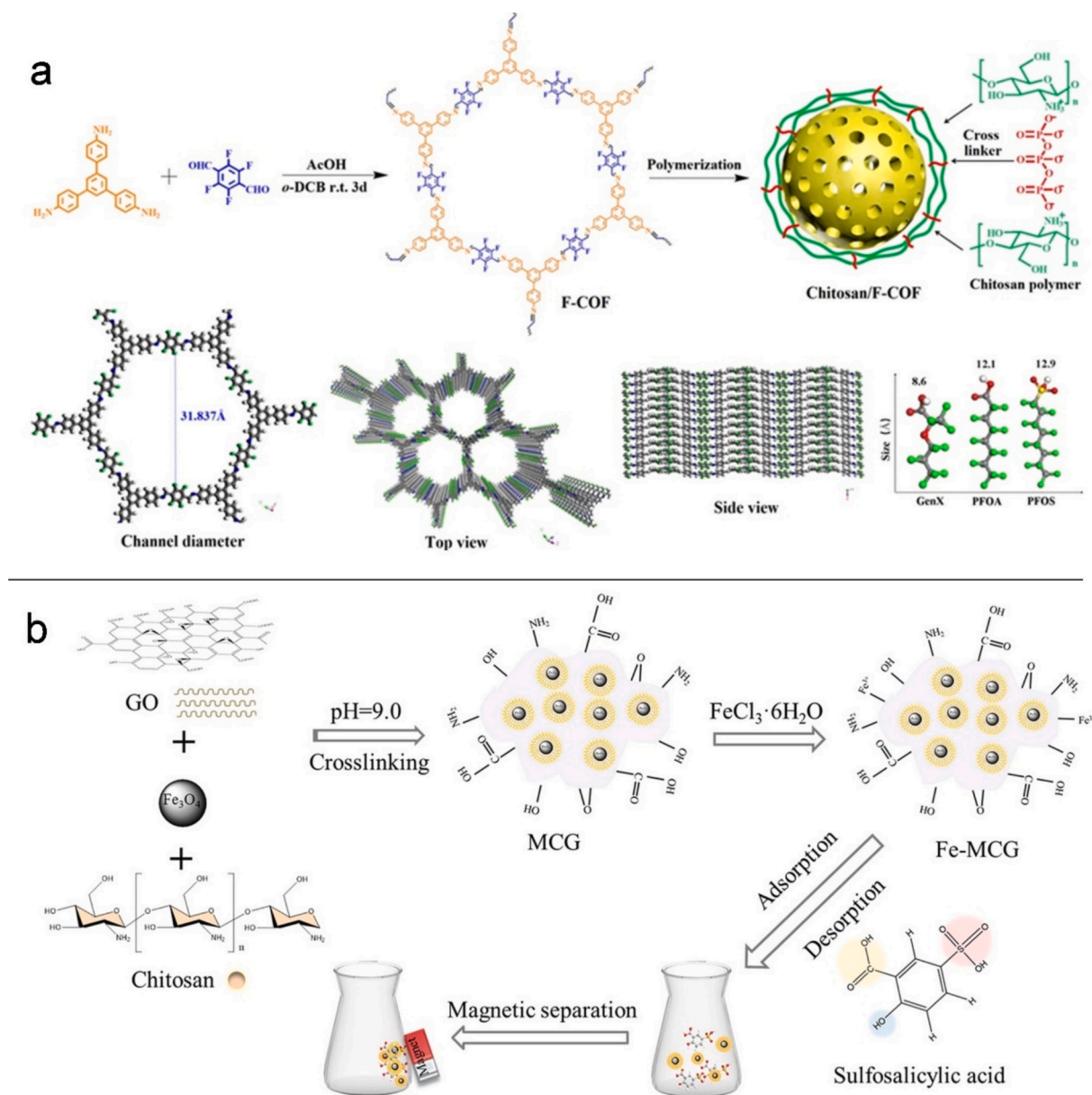


Fig. 4. a: Scheme for the synthesis of F-COF and chitosan-F/COF and F-COF's channel diameter top and side views [77] ; b: Fabrication diagram for the synthesis of Fe-MCG [81].

Given the coexistence of multiple contaminants in actual water environments, current research emphasizes the applicability of chitosan-based materials in authentic environmental water samples. For example, Shahrokhi et al. synthesized crushed grafted chitosan beads, which exhibited a maximum adsorption capacity of 230.03 mg/g for PFOA and 250.08 mg/g for PFOS [71]. In the presence of a PFAS mixed solution (PFOA, PFOS, PFBA, PFBS), the removal efficiency of PFOS and PFOA decreases by 0 % and 32.6 %, respectively. Additionally, another study synthesized graphene oxide-modified zinc ferrite-immobilized chitosan beads (rGO-ZF@CB) as adsorbents and investigated the impact of coexisting anions (chloride ions, sulfate ions, phosphate ions, and bicarbonate ions) [76]. Regarding the influence of rGO-ZF@CB on the adsorption of PFOA and PFOS in aqueous solutions, the findings revealed that the presence of chloride ions, sulfate ions, and phosphate anions in the mixed system diminishes the adsorption performance of rGO-ZF@CB. Conversely, in the case of bicarbonate, the adsorption efficiency remains relatively unaffected. Although this study primarily investigated the effect of inorganic anions on the adsorption of PFOA

and PFOS by rGO-ZF@CB, real-world wastewater often contains significant amounts of organic matter (e.g., humic acid, fulvic acid). These organic compounds may impact adsorption performance by competing for adsorption sites or altering the adsorbent's surface characteristics. Previous studies have shown that natural organic matter can significantly reduce the removal efficiency of perfluorinated compounds by adsorbents. Therefore, future research should focus on evaluating the influence of organic matter on the adsorption performance of rGO-ZF@CB to more accurately predict its effectiveness in practical applications.

Overall, chitosan's amino and hydroxyl functional groups can form stable complexes with PFAS molecules through hydrogen bonding and electrostatic interactions. In this review, chitosan-based adsorbents achieved a maximum adsorption capacity for PFOS of 8307.10 mg/g, which is significantly higher than traditional adsorbents. However, while chitosan-based materials have demonstrated high treatment efficiency within a pH range of 2.0–3.0 under experimental conditions, maintaining such a low pH is impractical for real-world wastewater

treatment. Future research should focus on optimizing treatment efficiency under neutral or near-neutral pH conditions to minimize the costs and operational complexity associated with pH adjustments. Moreover, integrating this method with existing treatment processes should be explored to enhance overall treatment efficiency.

4.1.2. Removing PPCPs from wastewater

PPCPs, as a class of emerging organic micropollutants, refer to the collective term for various chemicals found in medications and PPCPs used by humans, animals, and plants [82]. PPCPs primarily include antibiotics, non-steroidal anti-inflammatory drugs, psychiatric drugs, environmental estrogens, disinfectants, synthetic musks, anti-inflammatories, UV agents, and various other substances [83]. In fact, it has been reported that PPCPs encompass thousands of different compounds [84,85]. While PPCPs are often found in low concentrations within aquatic environments, their ecological ramifications remain substantial [86]. At low concentrations, most common PPCPs have the potential to cause intractable physiological defects [87]. Several methods for the removal of PFAS have been reported in the literature, including advanced oxidation methods (photocatalysis, ozonation, ultrasonic treatment, and electrochemical oxidation), membrane technologies (filtration, nanofiltration, and reverse osmosis), biodegradation (involving bacteria, fungi, and algae) and adsorption [58,82]. Among all these methods, adsorption is considered the ideal technique for PPCPs

removal due to its favourable operational characteristics, minimal secondary pollution, low cost, and multifunctionality [82].

Recently, significant attention has been paid to diverse polymer and biopolymer adsorbents [58,88,89]. Notably, chitosan and its derivatives have emerged as highly active, renewable, and cost-effective biosorbents for removing PPCPs from aquatic environments [58]. Through WOS searches, it is evident that in recent years, a substantial number of papers have utilized chitosan-based materials for the adsorption of PPCPs, with as many as 107 papers focused solely on antibiotics. Table 3 presents a selection of literature utilizing chitosan-based materials for the removal of PPCPs. Recent reports have indicated that mechanisms involved in the adsorption of PPCPs using chitosan-based materials primarily include electrostatic attractions, hydrogen bonding, and π - π electron-donor-acceptor (EDA) interactions, which is similar to the findings as shown in Table 3 [82,90,91]. The functional groups of chitosan (-OH and -NH₃) are capable of attracting PPCPs through electrostatic interactions and hydrogen bonding [90,91]. Besides, chitosan can be easily modified through physical or chemical methods to adsorption PPCPs through π - π EDA interactions [60]. Notably, a recent study suggests that the adsorption of PPCPs by chitosan-based materials may also involve a nucleophilic addition reaction, which is effective only under acidic conditions [91].

According to previous research, the primary influencing parameters for the adsorption of PPCPs by chitosan-based adsorbents include pH

Table 3
Comparison of adsorption capacities for PPCPs of chitosan-based materials (selected studies).

Adsorbent		NOP ^a	Adsorption Capacity		Regeneration		Removal mechanism	Ref.
Type	Cross-linkers		Suitable pH value	Q _{max} (mg/g)	Desorption eluents	Q _{DEMAX} ^b		
ZIF-67/ QGO/SB- CS	3-dimethyl ammonium propane sulfonate	1(tetracycline)	–	1375.00	CaCl ₂ solution	1300	The abundance of pores facilitates the chemisorption of PFAS onto aerogels.	[84]
PVA/CS/ SAP@PEI	polyethylenimine	1(diclofenac sodium)	5.0	493.81	NaOH solution	45	Electrostatic interactions and hydrogen bonding	[98]
EPCS@PEI	polyethylenimine	1(diclofenac sodium)	4.0	253.32	NaOH solution	14	Electrostatic interactions and hydrogen bonding	[99]
Fe3O4/AC/ chitosan	NaOH	3(ciprofloxacin; erythromycin; amoxicillin)	–	90.10; 178.57; 526.31	NaCl: ethanol (9:1,v:v)	–	–	[100]
Bentonite/ chitosan	NaOH	3(amoxicillin; ampicillin; doripenem)	–	51.90–86.10 66.10–83.30; 78.40–96.00	–	–	–	[101]
Ag ₂ S- Chitosan	trifluoroacetic acid	1(clindamycin)	2.0	181.28	NaOH solution	29	Electrostatic interactions	[90]
CSp	NaOH	1(cefotaxime)	4.0	648.05	NaOH solution	–	Electrostatic attraction, nucleophilic addition reaction, and hydrogen bonding	[91]
CSf	NaOH	1(cefotaxime)	4.0	1003.64	NaOH solution	953	Plane strengthening effect, electrostatic attraction, nucleophilic addition reaction, and hydrogen bonding	[91]
chitosan/ cellulose	liquid paraffin	tylosin	7.0	59.26	HCl solution	59	Electrostatic interactions, π - π EDA, internal diffusion, size-exclusion effect and hydrogen bonding	[102]
CMC-Mt	–	2(tetracycline; chlortetracycline)	4.0–7.0	178.57; 271.74	–	–	Cation exchange and electrostatic interaction	[103]
CS-MNPs	NaOH	2(ciprofloxacin; levofloxacin)	6.5	36.31; 32.22	NH ₃ solution	29	Electrostatic interaction, pore-filling effect, π - π EDA, and hydrogen bonding	[104]
Chi-SiO ₂ /Fe ₃ O ₄	–	1 (ciprofloxacin)	12.0	52.14	NaCl: ethanol (9:1 v:v)	–	–	[105]
MgO/Chit/ GO	–	2 (norfloxacin; ciprofloxacin)	7.0	1111.00; 1000.00	–	–	Electrostatic interaction, and π - π EDA	[106]
CIP-MCA	sodium tripolyphosphate	3(tetracycline; ciprofloxacin; amoxicillin)	6.0–8.0	753.20; 339.00; 135.40	Ultrapure water	–	–	[107]
DPCD-CS	–	1(Tetracycline)	11.0	223.84	KCl, H ₃ PO ₄ , (NH ₄) ₂ HPO ₄	67.04 %	Electrostatic attractions, hydrogen bonding, and π - π EDA	[108]
DPCA-CS	–	1(Tetracycline)	11.0	205.92	KCl, H ₃ PO ₄ , (NH ₄) ₂ HPO ₄	74.29 %	Electrostatic attractions, hydrogen bonding, and π - π EDA	[108]

value, adsorbent dosage, initial concentration of pharmaceutical compounds, and temperature [57,92]. Among these parameters, the pH value significantly impacts the adsorption of PPCPs, exerting a substantial influence on the removal process [44]. This is because the pH value affects the surface charge of the adsorbent, as well as the ionization and morphology of the adsorbate [57]. Previous investigations have extensively discussed this aspect [44,57]. However, it has been observed that these discussions often overlook the significant influence of pH value on the electronegativity of the adsorbent itself. This phenomenon is attributed to the presence of the point of zero charge pH (pH_{pzc}) [93]. When the pH value of the solution is lower than the pH_{zero} , the adsorbent typically carries a positive charge, enabling it to adsorb negatively charged ions and vice versa [94].

Common modification methods for chitosan-based materials include metal modification, magnetic modification, clay modification, and carbon modification [95]. Recently, magnetic chitosan has garnered significant attention owing to its facile magnetic separation and subsequent solid-liquid separation following the elimination of diverse PPCPs. Moreover, the incorporation of magnetic composite materials into chitosan has the potential to enhance both adsorption rate and efficiency. For instance, Mashile et al. prepared cellulose-chitosan nanohydrogels achieved up to 98 % removal efficiency for propranolol hydrochloride, atenolol, and carbamazepine [96]. Furthermore, the hydrogel exhibited remarkable reusability for up to ten cycles, retaining a removal efficiency exceeding 80 %. The augmentation of basal planes and interlayers within the amalgamation of magnetic chitosan and clay materials has proven advantageous for enhancing the adsorptive capability of the material [57,97]. The elongated chains inherent in the organoclay induce a rise in interlayers, fostering the development of robust hydrophobic interactions between magnetic chitosan and organic contaminants [57,97]. Besides, another research has successfully synthesized a magnetic composite incorporating graphene oxide, chitosan, and organoclay (GO/mCS/OC), revealing an impressive removal efficiency of up to 98 % for triclosan [97]. Nevertheless, the preparation of GO/mCS/OC is characterized by a heightened level of intricacy attributable to the associated preparation costs.

In short, while there are many studies on the removal of PPCPs by chitosan-based materials, it is important to recognize that in actual wastewater systems, the concentrations of these compounds are significantly lower, and they coexist with various other typical organic compounds. Therefore, numerous studies on practical systems have clearly demonstrated that key contaminants cannot be removed entirely. Although chitosan-based materials have shown maximum adsorption capacities more significant than 1000 mg/g in model systems, their practical application potential may be limited. To address this issue, pilot-scale research is essential for evaluating the efficacy of chitosan-based adsorbents under real wastewater treatment conditions. By focusing on both the challenges and opportunities in practical applications, future research can make more meaningful and valuable contributions to environmental purification processes.

4.1.3. Applications of solar evaporation in water purification

As shown in Fig. 5, Chitosan-based composites have garnered extensive interest for their potential to optimize solar evaporator architectures, thereby enhancing desalination efficiency [109–111]. For instance, Li et al. [112] introduced lignin carbon quantum dots into chitosan aerogels, substantially augmenting light absorption and photothermal conversion while improving hydrophilicity. As a result, the resulting aerogels exhibited markedly increased water evaporation rates and salt resistance, demonstrating excellent performance in evaporating and purifying high-salinity brine and heavy metal-laden wastewater. In another study, a vertically porous chitosan aerogel fabricated via liquid-nitrogen-assisted freeze-drying significantly improved water transport and salt diffusion, leading to high-efficiency solar evaporation [113]. Furthermore, Arunkumar et al. [114] developed a chitosan aerogel-graphene nanosheet composite that combines photothermal

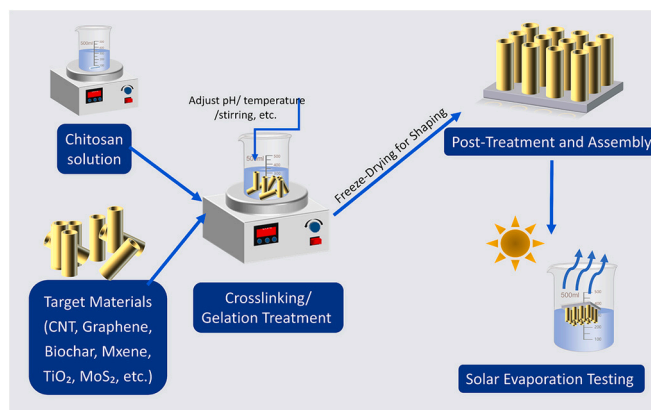


Fig. 5. Fabrication process of chitosan-based photothermal solar evaporator.

absorption and phase-change energy storage, achieving a high light absorption efficiency (up to 93.4 %) and robust stability under continuous operation. By filling waste aluminium cans with soybean wax, the system facilitated efficient heat storage and release, yielding a freshwater production rate of 4.1 L/m². Gao et al. [115] advanced this concept by engineering a black hydrogel based on g-C₃N₄, loofah fibre, and chitosan. Under a 3.5 wt% NaCl solution, this hydrogel demonstrated an evaporation rate of 2.1 kg/m²·h and maintained a 91.4 % tetracycline degradation rate over six hours, underscoring its synergistic capabilities for desalination and pollutant remediation. Similarly, Chen et al. [116] subsequently proposed a chitosan-polyvinyl alcohol composite hydrogel featuring a Janus structure via the incorporation of both hydrophobic and hydrophilic silica nanoparticles. This design imparts a hydrophobic surface while retaining a hydrophilic underside, effectively mitigating heat loss and substantially enhancing salt resistance and water transport. In simulated seawater, the resulting composite attained an evaporation rate of 1.58 kg/m²·h and an evaporation efficiency of 88.63 %, approximately 1.6 times higher than the unmodified control, thereby offering new prospects for solar-driven desalination.

Despite the promising applications of chitosan-based composites in solar evaporation systems, several challenges remain. As a natural biopolymer, chitosan may undergo structural degradation over extended exposure to highly saline and chemically complex environments, potentially undermining long-term stability. Additionally, the material's biodegradability could limit operational lifespan, raising concerns regarding durability. Meanwhile, efforts to enhance photothermal conversion and water transport often rely on complex fabrication protocols and elevated costs, thereby constraining large-scale industrial implementation. Consequently, future research should seek a balance between optimizing performance and minimizing manufacturing expenses while also exploring multifunctional design strategies to bolster the stability, antifouling capacity, and broader applicability of chitosan-based composites for real-world water treatment demands.

4.2. Preparation of chitosan-based composite materials

As mentioned in Section 4.1.2, typical modification techniques for chitosan-based materials encompass metal modification, magnetic modification, clay modification, and carbon modification [95]. More specifically, chitosan molecules can readily amalgamate with diverse materials, including polysaccharides (cellulose and cyclodextrin), carbon nanotubes, graphene, graphene oxide(GO), metal-based nanoparticles, covalent organic frameworks (COF), metal-organic frameworks (MOF), clay composite materials, metal sulfide composite materials and molecularly imprinted polymers (MIPs), thereby engendering innovative smart macromolecular platforms to remove contaminants [89,117,118]. These applications extend beyond water and

wastewater treatment to encompass diverse fields, including pharmaceuticals, medicine, textiles, food, and sensors. Consequently, numerous research groups are at the forefront of propelling future advancements, leveraging chitosan-based materials in domains like physical and organic chemistry, materials design, and water engineering.

4.2.1. Development of chitosan@GO composite materials

The low mechanical strength, poor heat resistance, limited stability, weak acid resistance, low solubility, and low surface area of chitosan restrict its widespread application in the field of water treatment [119,120]. Numerous studies have indicated that preparing composite materials of chitosan with carbonaceous materials such as activated carbon, biochar, carbon nanotubes, GO, and graphene can effectively circumvent these issues [53,121,122]. Compared to other carbonaceous materials, GO epitomizes an emerging form characterized by outstanding thermal, electrical, and mechanical properties [119]. Furthermore, it exhibits a notably larger specific surface area of 2630 m²/g, π electronic system, and abundant oxygen-containing functional groups, making it exceptionally efficient as an adsorbent [120,121,123,124].

Indeed, GO demonstrates proficiency in adsorbing contaminants through electrostatic, ion exchange, π - π interactions, and hydrophobic interactions [125]. It has been reported that GO maintains a negative charge across a broad pH spectrum (between 2 and 11) due to the presence of acidic groups (-COOH), enabling the adsorption of metal cations, cationic dyes, and other cations through electrostatic molecular interactions [121]. Furthermore, π - π interactions play a crucial role in enhancing the adsorption of aromatic compounds by GO [126]. Nevertheless, the robust π - π interaction among GO sheets may lead to their aggregation in aquatic environments, diminishing the surface area and adsorption efficiency, thereby constraining its broader application in wastewater treatment [120]. Chitosan may serve as an adjunct material to mitigate the aggregation of GO sheets and enhance their recyclability. In the composite, the -COOH groups of GO can interact with the -NH₂ groups of chitosan through hydrogen bonding and electrostatic interactions, as illustrated in Fig. 6 [119,127]. This interaction leads to the enhanced adsorption performance of GO@chitosan composite materials compared to any individual component.

Chemical modifications, such as cross-linking and grafting, can introduce various functional groups into chitosan/GO, enhancing its adsorption capacity for contaminants [121,128,129]. For instance, Xia et al. employed a hydrothermal method to prepare a phytic acid-modified chitosan/GO composite (PCG), revealing a remarkable maximum adsorption capacity for U(VI) at 325.56 mg/g [130]. Besides, it has been reported that PCG's hydroxyl and phosphate groups form

robust chelates with U(VI), demonstrating high adsorption selectivity. Another study by Jeyaseelan's group involved the synthesis of amine-functionalized GO-modified chitosan (AGO@CS) adsorbent, exhibiting a notable maximum adsorption capacity for F⁻ ions that reached 4650 mg/kg [131]. As reported, the defluorination mechanism of AGO@CS relies solely on electrostatic attraction.

In addition to introducing functional groups into chitosan/GO, incorporating magnetic nanomaterials into chitosan/GO composites has also been demonstrated as an efficacious approach for achieving solid-liquid separation [82,132]. Iron element is known for its abundance in the Earth's crust, cost-effectiveness, and environmentally friendly nature [82]. Fe₃O₄, the most prevalent magnetic material, is frequently synthesized through the co-precipitation of Fe³⁺/Fe²⁺ solutions. For instance, using the co-precipitation technique, Liu et al. fabricated a Fe (III)-enriched magnetic chitosan/GO composite (Fe-MCG) [81]. The synthetic procedure of Fe-MCG is depicted in Fig. 4b. The findings indicate that Fe-MCG exhibits a maximum adsorption capacity of 135 mg/g for sulfosalicylic acid that can be employed for multiple adsorption cycles. Additionally, A. Ahmed's team prepared chitosan/GO/copper ferrite through the Cu(II) and Fe(III) solution precipitation method, demonstrating adsorption capacities of 112.6 mg/g for indigo carmine and 66.15 mg/g for safranin O [133]. Overall, introducing magnetic substances through co-precipitation represents a straightforward and cost-effective approach to designing multifunctional materials.

4.2.2. Development of chitosan-based MIPs

Unlike commercial adsorbents such as CAC and zeolites, commercial adsorbents can efficiently remove significant quantities of non-trace contaminants from wastewater [134]. MIPs prove advantageous in addressing trace contaminants as they can be precisely tailored to eliminate singular or multiple target compounds [135]. Besides, the physical properties of chitosan are suboptimal, accompanied by a pronounced tendency to swell significantly in aqueous systems, which constrains its practical utility [118,136]. Indeed, chitosan can undergo reactions with diverse cross-linking agents, including aldehydes, heterocyclic compounds, ethers, amides, and acids, forming covalent bonds or engaging in electrostatic interaction [100]. Therefore, chemical cross-linking emerges as a potent technique for fabricating chitosan-based MIPs that is frequently employed to surmount the abovementioned limitations. The fundamental tenet of molecular imprinting technology involves the judicious selection of suitable functional monomers amalgamated with template molecules (contaminants) to yield MIPs [118]. Following this, the elution of template molecules occurs, with MIPs exhibiting dimensions, configurations, and functional group orientations precisely aligned with the binding site of the target molecule

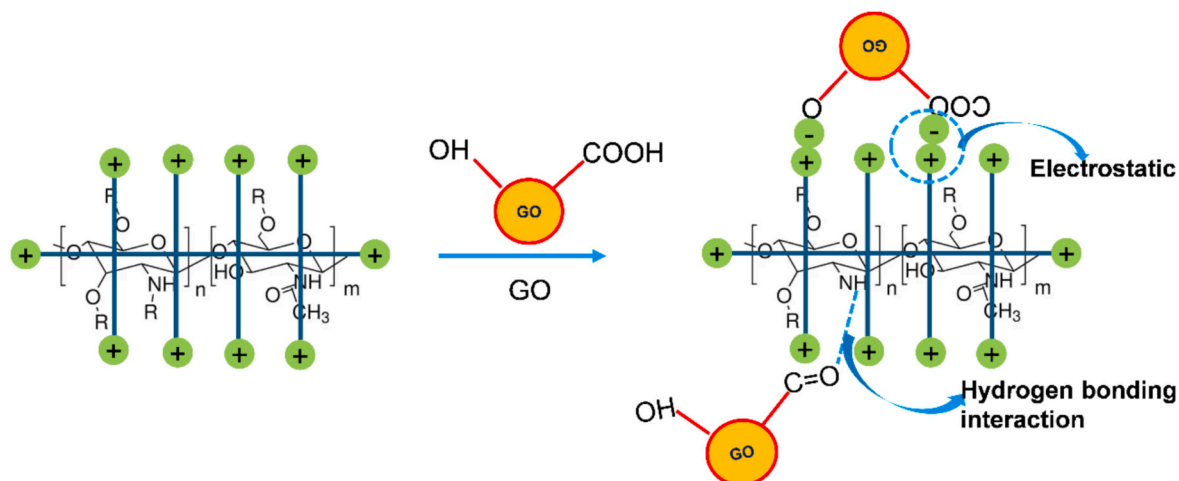


Fig. 6. The mechanism involves hydrogen bonding and electrostatic interactions between GO and chitosan. Modified from [69].

[137]. The MIP preparation process is shown in Fig. 7.

Compared with traditional adsorbents, MIP technology shows extraordinary results in adsorbing micropollutants. Yang et al. investigated pharmaceutical treatment in hospital wastewater, achieving success in creating the J-MIP3 fixed-bed column enabling the swift extraction of propranolol [138]. The removal efficiency of propranolol exceeds 90 %, and the treatment efficiency is higher than that of activated carbon fixed bed columns. Extensive research on interfering substances and reusability was undertaken, with findings indicating the practical efficacy of J-MIP3, offering a novel approach to hospital wastewater management. Similarly, another study reported a Cu(II) ion-imprinted polymer prepared using three-dimensional GO-based porous materials and imprinting technology, which has high selectivity, high adsorption capacity, and good reusability, compared with other adsorbents (membranes, hydrogels, etc.) have the highest adsorption capacity (112 mg/g) and low concentration adsorption efficiency [139]. Furthermore, Tang et al. [140] developed a molecularly imprinted catalyst (3D-MIC) for the targeted removal of organic micropollutants from wastewater. The 3D-MIC exhibited robust selectivity with an imprinting factor above 2.04 and an adsorption capacity enhanced by 2.7 times compared to conventional adsorbents, achieving over 91 % removal efficiency for sulfamethoxazole (SMX) in real water samples. While MIP technology demonstrates remarkable efficiency in selective micropollutant adsorption, its practical application may be constrained by factors such as synthesis complexity, cost, and limited adsorption capacity for broader pollutant removal. Traditional adsorbents like biochar and activated carbon, despite their lack of molecular recognition, often provide a more cost-effective and scalable solution for large-scale wastewater treatment [141].

4.2.3. Development of chitosan@metallic oxide photocatalyst

Metallic oxide photocatalysts typically refer to metal oxide semiconductors, including but not limited to TiO_2 , $\text{CuO/Cu}_2\text{O}$, CoFe_2O_4 , NiFe_2O_4 , and Ag_3PO_4 [142,143]. These materials exhibit irregular characteristics and possess diverse applications in sensor technology, catalysis, and dye batteries, among other functionalities [143]. Owing to its elevated photosensitivity, non-toxic, economic viability, and environmental friendliness, metallic oxide photocatalysts find primary application in heterogeneous photodegradation of organic contaminants and photocatalytic environmental remediation for wastewater purification [142–144]. Nevertheless, the application of these semiconductors

faces constraints due to their inadequate adsorption capacity and poor stability in aqueous environments [145,146]. Consequently, various additives or supports, such as activated carbon, carbon nanotubes, silica, and polymers, have enhanced both photocatalytic activity and stability [142]. Employing the natural biopolymer chitosan as a matrix emerges as an effective strategy to surmount the limitations associated with metallic oxide photocatalysts, addressing concerns related to stability, recyclability, homogeneity, active surface, and agglomeration [143–146]. Integrating chitosan with metallic oxide photocatalysts has found widespread use in degrading organic contaminants and reducing metal ions.

According to CiteSpace statistical data, TiO_2 /chitosan is the most prevalent catalyst employed. Chitosan serves as a carrier for TiO_2 , which effectively addresses the intricate challenges associated with selecting and recycling nanomaterials in photocatalysis. Through its capacity to adsorb pollutant molecules and consistently furnish TiO_2 for photo-degradation, chitosan mitigates electron-hole recombination (Fig. 8) [147]. Commercial chitosan manifests in various physical forms, where it can undergo precipitation to yield beads, casting for the formation of films and membranes, spinning to fabricate fibres, and cross-linking to generate gels, fibres, or sponges [148]. In recent years, numerous scholars have fabricated TiO_2 /chitosan thin films to attain elevated pollutant removal rates through collaborative adsorption/photo-degradation mechanisms. As an illustration, Hoang et al. employed 3D printing technology to fabricate chitosan/nano- TiO_2 films to degrade methylene blue [149]. Vigneshwarand et al. fabricated thin films by integrating TiO_2 onto a cellulose/chitosan matrix to degrade Metanil Yellow [146]. Gubitosa et al. fabricated chitosan-based films incorporating TiO_2 to remove 2,4-dinitrophenol [145]. While there has been some advancement in the pertinent research concerning chitosan/metallic oxide photocatalysts, certain limitations persist within the catalytic system, notably encompassing challenges related to protonation, photoactivation, and catalyst recovery [150]. Subsequent advancements could address the abovementioned limitations by incorporating noble metal doping into composite materials and loading them into appropriate carriers.

4.2.4. Development of chitosan/clay composite materials

Chitosan can form stable composite materials with various types of clays, such as montmorillonite, kaolinite, and bentonite, and has been extensively utilized in pollutant removal in diverse forms, including

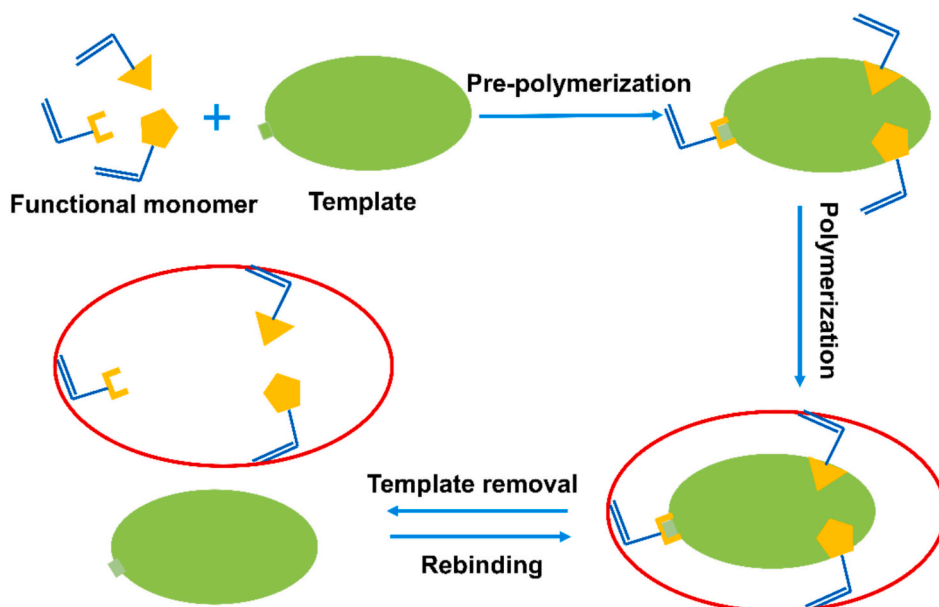


Fig. 7. Schematic representation of the molecular imprinting process. Modified from [118].

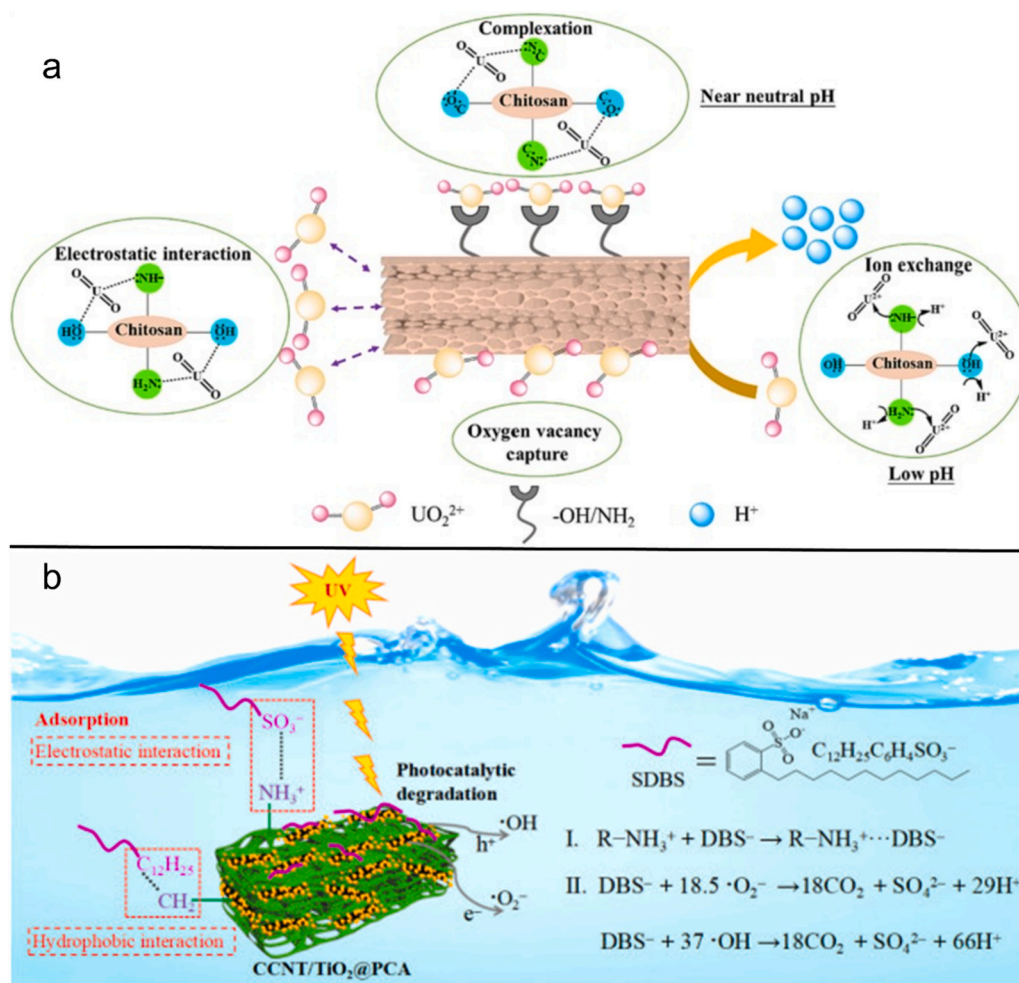


Fig. 8. Mechanism of TiO₂/chitosan in contaminants removal (a:U(VI) [151]; b: anionic surfactants [152]).

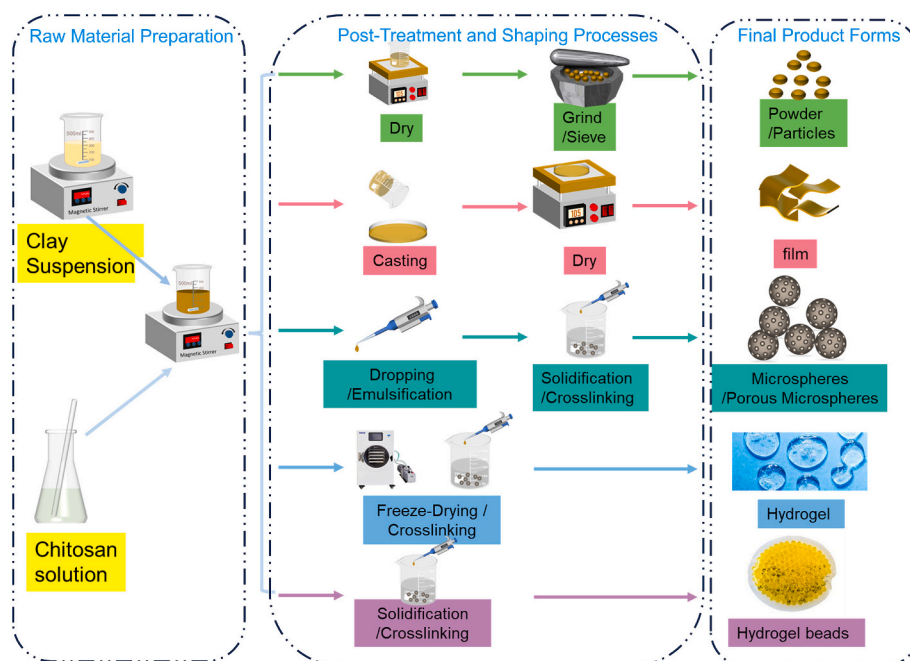


Fig. 9. Various fabrication techniques enable the chitosan-clay composite to be produced in diverse forms.

films, hydrogels, beads, and nanocomposite structures [153]. As illustrated in Fig. 9, the synthesis of chitosan/clay composites generally involves raw material preparation, post-treatment, and shaping processes, culminating in the formation of the final product [154]. Initially, a clay suspension and a chitosan solution are prepared through magnetic stirring and subsequently homogenized. Depending on the intended application, various processing techniques, such as drying, grinding, film casting, dropwise curing, or freeze-drying, are employed to obtain the composite in different morphological forms, including powders, films, microspheres, or hydrogels. These diverse material forms enable a wide range of applications in adsorption, water purification, biomedical fields, and catalysis.

It has been reported that pH is a critical determinant influencing both the final morphology and adsorption performance of the synthesized composite [154]. Under acidic conditions, positively charged chitosan interacts with negatively charged clay through electrostatic attraction, facilitating interactions between the composite and metal ions or dye molecules [155–157]. However, excessively low pH levels may cause H⁺ ions to compete with target contaminants for adsorption sites, thereby reducing adsorption efficiency [154,158]. Conversely, at higher pH levels, chitosan tends to lose its positive charge, weakening its interaction with clay [159]. Therefore, to optimize both adsorption performance and material synthesis, maintaining a near-neutral pH is recommended, as this preserves the positive charge of chitosan, enhances electrostatic interactions with clay, and prevents undesirable precipitation [160]. Additionally, another study has highlighted that the final morphology of the composite (e.g., hydrogel, film, or bead structure) and the molecular weight of chitosan significantly impact adsorption performance [161,162]. Lower molecular weight chitosan interacts more readily with clay layers, forming stable structures, whereas higher molecular weight chitosan with a greater degree of deacetylation tends to promote hydrogel formation [162]. Hence, selecting an appropriate chitosan molecular weight is essential to achieving the desired composite morphology and optimizing its adsorption characteristics.

The application of modified chitosan-clay composites has progressively expanded to the removal of multiple pollutants, including heavy metal ions (e.g., Pb(II), Cr(VI)), organic dyes (e.g., methylene blue, Congo red), and inorganic contaminants (e.g., phosphate, fluoride ions) [154,163]. Research indicates that the adsorption capacity of clay–chitosan composites for both cationic and anionic dyes in wastewater is significantly influenced by the surface charge of clay minerals, inter-layer spacing, and modification methodologies. For instance, a composite comprising 30 % chitosan and 70 % clay, when subjected to optimized reaction conditions (including a pH range of 2–4, a stirring rate of 600 rpm, and a contact time of 60 min), effectively removes methylene blue and Congo red, achieving maximum adsorption capacities of 97.08 mg/g and 80.9 mg/g, respectively [164]. Additionally, another study reveals that chitosan–montmorillonite composites demonstrate optimal adsorption performance for methylene blue under alkaline conditions (pH 9.5), with a maximum adsorption capacity of 158.79 mg/g [165]. This multilayer adsorption process is governed by hydrogen bonding and π – π interactions. Furthermore, employing different types of clay and various modification techniques enhances the stability and mechanical strength of the composites, rendering them suitable for the treatment of high-concentration dye wastewater. A review of recent literature reveals a growing number of studies similar to those mentioned above. However, current research still faces significant challenges regarding the mechanical strength, solution stability, and regeneration efficiency of chitosan/clay composites. Moving forward, key research directions in this field will include optimizing fabrication processes, enhancing the multidimensional stability of composite materials, and exploring cost-effective and highly efficient regeneration strategies.

4.2.5. Development of chitosan/metal sulfide composite materials

Numerous studies have explored the incorporation of metal sulfides into chitosan-based materials for the remediation of various wastewater contaminants. Chitosan/metal sulfide composites have been reported to not only efficiently remove pollutants through adsorption but also exhibit remarkable antibacterial properties [166–168]. For instance, Li et al. [167] demonstrated that under optimized conditions (pH 6, shaking time of 120 min, MO concentration of 70 mg/L, and temperature of 35 °C), these composites achieved removal efficiencies of 98.9 % for NiS and 93.4 % for CuS. Additionally, these composites exhibited excellent antibacterial activity against *Staphylococcus aureus* (*S. aureus*) and notable inhibitory effects on *Escherichia coli* (*E. coli*), highlighting their potential as multifunctional materials for wastewater treatment applications. Similarly, Nagakrishna and Tirupanyam [169] investigated FeS₂/chitosan composites and found that they exhibited excellent performance in Cd(II) ion removal while also demonstrating significant antibacterial activity against *E. coli*.

In addition, several investigations have centred on the potential of chitosan/metal sulfide composites for photocatalytic pollutant degradation and antibacterial applications. For example, Wang et al. [170] successfully fabricated Ag₂S/NiTiO₃/chitosan nanocomposites capable of achieving complete degradation of metronidazole under visible-light irradiation while exhibiting pronounced inhibitory effects against *Streptococcus pneumoniae* and *Escherichia coli*, thereby demonstrating excellent antibacterial properties. Similarly, Janani et al. [171] developed ZnS-CuO/PVA/chitosan nanocomposites that achieved a 94.7 % degradation rate of tetracycline under visible-light irradiation, significantly outperforming ZnS or CuO alone. This composite also displayed favourable antibacterial activity toward *E. coli* and *Bacillus subtilis*, further underscoring its potential in wastewater treatment. Moreover, Ikram et al. [172] prepared C₃N₄-doped CdS/chitosan composites, reporting a photocatalytic degradation efficiency of 99.75 % for methylene blue—substantially higher than that of conventional CdS materials (85 %)—along with outstanding antibacterial efficacy against *E. coli* and *Staphylococcus aureus*. Collectively, these findings highlight the broad application prospects of chitosan/metal sulfide composites as versatile multifunctional materials.

Nevertheless, although these studies underscore the considerable potential of chitosan/metal sulfide composites for photocatalytic degradation and antibacterial applications, several challenges warrant further investigation. First, the complex and costly nature of current fabrication methods constrains the practical deployment of these composites. Accordingly, the development of more streamlined and cost-effective synthesis protocols constitutes a pivotal direction for future research. Second, most existing studies focus on the degradation of a single pollutant, whereas real-world wastewater commonly contains multiple contaminants. Exploring the synergistic treatment of complex pollutant mixtures would thus be more representative of practical scenarios. Third, the long-term stability of the photocatalytic response and the durability of the antibacterial effect remain insufficiently examined, potentially limiting large-scale application. Furthermore, environmental safety merits closer scrutiny, particularly regarding the release of metal ions during use and the attendant ecological risks. Future research efforts should concentrate on the continued optimization of composite performance, coupled with the integration of actual water treatment processes, to foster a comprehensive evaluation and facilitate the widespread implementation of these materials in water pollution remediation.

4.3. Application of ML in the optimization of chitosan wastewater treatment

Conventional modelling and optimization techniques employed in the realm of uptake of adsorbates by suitable adsorbents, such as response surface methodology (RSM) and statistical methods, necessitate extensive experimental endeavours, entailing high costs and time

consumption [173,174]. Conversely, data-centric ML approaches are potent instruments for investigating the intricate connections between adsorption efficacy and adsorbates [175]. ML algorithms find extensive application in scrutinizing the intricate interplay among the characteristics of adsorbents, adsorption conditions, and adsorption efficacy, eschewing the need for empirical assumptions [176,177]. Additionally, ML can be harnessed to construct models for the adsorption of contaminants onto adsorbents.

Fig. 10 presents a general flowchart of the ML process. Regarding the role of ML in chitosan applications, the removal performance of contaminants of chitosan-based materials can be predicted and explained through ML modelling based on high-dimensional data and by considering different types of factors [178]. As shown in Table 4, although most of the data sets of ML are small, the prediction performance is still better than 0.9345. For example, Sun et al. used artificial neural networks (ANN) to predict the removal effect of chitosan-based materials on heavy metals and dyes [179]. They found that ANN achieved the highest accuracy ($R^2 = 0.947-0.995$) and determined the best experimental conditions. In addition, Ciğeroğlu et al. applied ML to optimize the removal process of cefixime with chitosan-based materials [180]. The study found that the random forest (RF) model gave higher values than other models ($R^2 = 0.9939$), and the pH value was the most important factor affecting the adsorption capacity. However, most current studies use ANN models, and it is recommended that different ML algorithms be widely used for training/testing and that appropriate prediction models be carefully selected.

Hybrid models may be a promising strategy to improve model prediction performance. Flores-Gómez et al. proposed ANN combined with the improved grey wolf optimization (IWGO) metaheuristic algorithm (ANN-IWGO), achieving a correlation coefficient of $R^2 = 0.99$ [181]. Similarly, Naghibi et al. used an adaptive neural fuzzy inference system (ANFIS)-ANN to predict the dye removal efficiency of chitosan-based materials [180]. They stated that the Root mean square error and R^2 achieved by the ANFIS-ANN model were obtained at 0.01822 and 0.9958 for the test data, respectively, which was more accurate than the ANN prediction. Model-based explanations indicate that residence time is a decisive influencing factor. However, compared with the application of ML in other adsorbents (biochar and activated carbon), it is still

insufficient and lacking. The possible reason is that the structural characteristics and chemical properties of chitosan-based materials cannot be quantitatively displayed. While model systems can certainly be analyzed using ML, the technology is not yet advanced enough to effectively manage complex real-world systems. It will likely take several more years for these methods to mature to that level.

Although ML methods have demonstrated considerable success in certain domains, such as image recognition, their application in chitosan-based water treatment remains constrained by several limitations, including the scarcity of datasets, challenges in selecting key variables, and insufficient adaptability to diverse pollutant systems. Moreover, existing research has predominantly focused on model prediction, with comparatively limited attention given to the mechanistic interpretability of ML models, the rationality of feature selection, and the generalizability of these approaches in practical applications. For instance, Lu et al. [182] employed a RF model to predict the heavy metal removal efficiency of chitosan-based flocculants (CBFs), achieving high predictive accuracy ($R^2 = 0.9354$, RMSE = 5.67). However, the study was constrained by a small dataset (21 CBFs, 484 data points) and did not incorporate critical environmental variables, such as temperature and competing ions, which may significantly impact the model's robustness and generalizability. Similarly, Shukla et al. [22] combined ML with RSM for dye adsorption optimization, where the stacking model outperformed individual models ($R^2 = 0.94$, RMSE = 8.12). Despite this, external validation with real wastewater samples was lacking, reducing the model's applicability. Expanding on these approaches, Khajavian and Ismail [183] developed a deep eutectic solvent (DES)-modified polyvinyl alcohol/chitosan (PVA/CS) thin film membrane, integrating ML and density functional theory (DFT) calculations to optimize brilliant green (BG) dye adsorption. While their RF model achieved high accuracy ($R^2 = 0.93$), the study faced challenges in validating ML predictions against real wastewater conditions, underscoring the need for experimental integration. These studies highlight the potential of ML in adsorption-based water treatment but also emphasize the necessity for larger datasets, mechanistic insights, and real-world validation to enhance model reliability and practical applicability.

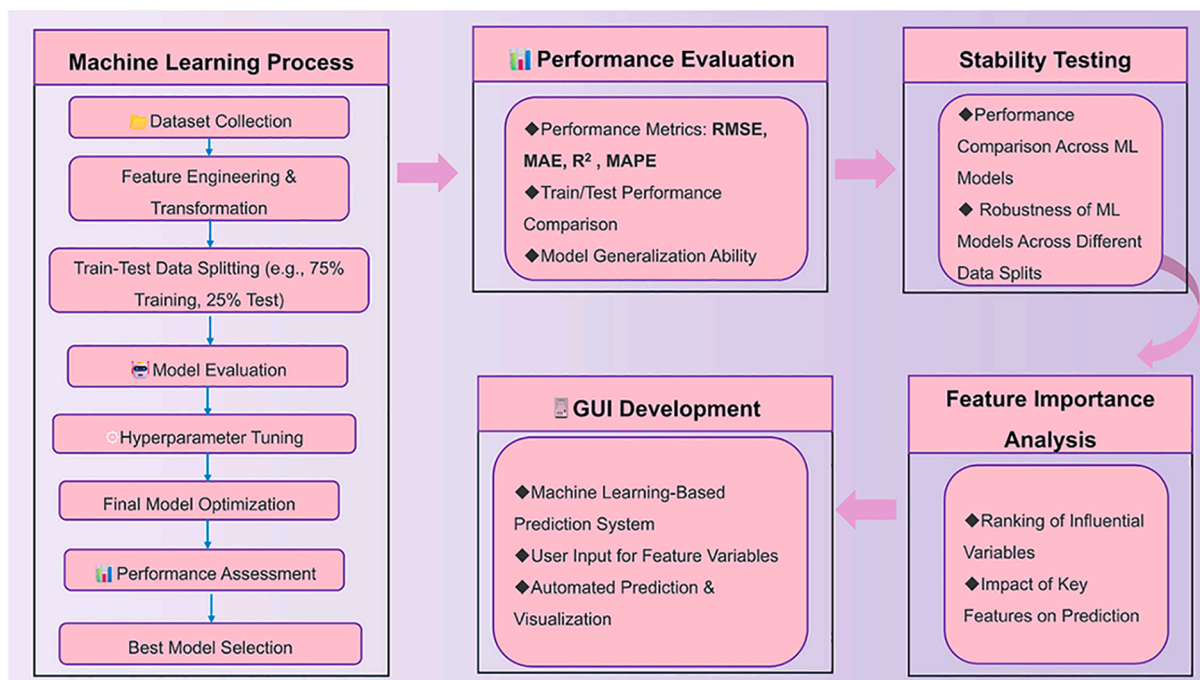


Fig. 10. Flowchart of the ML process.

Table 4

Optimization method and parameter optimization of chitosan in removing pollutants in water.

Absorbent type	Number of input parameters	Predicted pollution type	ML models	Data size	Prediction performance		Ref
					R2 (train/test)	RMSE (train/test)	
chitosan-based material	12	metal ions	RF, ANN	484	/0.9354	/5.67	[182]
chitosan/polyvinyl alcohol/zeolite imidazolate	5	dye	MLP-ANN, ANFIS	90	/0.9958	/0.01822	[180]
β -cyclodextrin grafted multi-walled carbon nanotubes/chitosan	5	dye	LS-SVM, GRNN	50	/0.999	/0.023	[184]
Chitosan/Resole/Pectin Aerogel	5	dye	ANN, ANN-IGWO	–	/0.9997	/0.3333	[181]
chitosan-magnetic material	6	metal ions	ANN	41	0.9315 / 0.9205	$1.14 \times 10^{-3} / 1.18 \times 10^{-3}$	[179]
chitosan-based material	5	dye	ANN	–	0.9789/0.9905	/2.9818	[185]
magnetic nanoparticles-rGO-chitosan	4	PPCPs	ANN, RF	20	/0.9939	/1.2404	[186]
Cinnamon-Bentonite Loaded Chitosan	4	dye	ANN	–	0.9966/0.9995	–	[187]
vinyl alcohol/chitosan	4	PPCPs	ANN, GRNN	30	0.9993/0.0058	/0.237	[188]
chitosan-based material	2	metal ions	ANN	840	/0.999	/0.0789–0.0888	[189]

Note: The highlighted in yellow represents the best model among the ML models, and the prediction performance value refers to the best model.

RF: Random Forests; ANN: Artificial Neural Networks; MLP-ANN: Multilayer Perceptron Artificial Neural Network; ANFIS: Adaptive Neuro-Fuzzy Inference System; LS-SVM: Least Squares Support Vector Machines; GRNN: Generalized Regression Neural Network; ANN-IGWO: Artificial Neural Network with Invasive Weed Optimization.

5. Current challenges and future research directions

5.1. Current challenges

Chitosan-based materials have been extensively studied as low-cost, efficient, and natural polymers for water treatment applications, including the adsorption of metal cations, dyes, anions (such as fluorides and phosphates), drugs (e.g., antibiotics), and various other organic contaminants. They also function as photocatalysts for the synergistic removal of organic contaminants through combined adsorption and degradation processes and serve as biofloculants. However, despite the breadth of research, several significant challenges hinder the practical application of chitosan-based materials:

- (1) Although many studies demonstrate excellent performance of chitosan-based materials under controlled laboratory conditions, these do not always reflect complex real-world environments. Factors such as competing ions, pH fluctuations, and natural organic matter can significantly affect removal efficacy, making it difficult to replicate lab-scale success in large-scale field applications.
- (2) Despite chitosan-based materials demonstrating excellent adsorption performance in controlled laboratory settings, there is a notable gap in systematic, large-scale validation studies. In particular, few experimental setups closely emulate real wastewater matrices, which often exhibit high variability in ionic composition, pH, organic matter content, and flow dynamics. This mismatch between lab-scale conditions and real-world environments makes it challenging to replicate the reported high removal efficiencies and cost-effectiveness at a larger scale. Consequently, scaling up the production of chitosan-based materials and achieving consistent performance in diverse environmental matrices remain major hurdles. The lack of pilot-scale or field demonstrations dampens broader commercial interest, as the transition from lab to field invariably reveals unforeseen operational difficulties, such as material fouling, fluctuating flow rates, and competing ions. These factors underscore the urgent need for systematic pilot-scale trials to capture the complex interplay of variables, thereby guiding the development of reliable, cost-effective processes suited for industry and municipal applications.
- (3) Compared to other commercially available materials, such as activated carbon and biochar, chitosan-based materials may not always offer sufficient economic benefits for water treatment

applications. Consequently, it may be necessary to explore niche applications or develop synergistic strategies (e.g., composites with other materials) to enhance their overall performance and justify their cost relative to established technologies.

- (4) The extraction and processing of chitosan typically involve chemical treatments with potential adverse effects on the environment. Moreover, the regeneration of chitosan-based materials often requires large quantities of chemical reagents, leading to secondary pollution, increased operational costs, and challenges in achieving environmentally benign regeneration processes.
- (5) The primary source of chitosan is chitin, predominantly derived from crustacean shells. Compared to other biomass sources, the availability of chitin is relatively limited, and its extraction is resource-intensive. This raises concerns regarding the sustainability and environmental impact of large-scale chitosan production, especially in the context of agricultural development and sustainable biomass utilization.

5.2. Areas of future development

- (1) Building on the established success of chitosan in adsorbing a wide range of waterborne contaminants, future research should explore alternative and more specialized applications of chitosan-based materials. For instance, recent progress in molecular imprinting technologies highlights the potential for molecularly imprinted chitosan, which can target specific trace pollutants. To validate these emerging materials, bench-scale experiments mimicking real effluent compositions (e.g., varying pH, ionic strength, and co-existing organics) should be complemented by pilot-scale tests in industrial or municipal wastewater treatment facilities. These larger trials would not only confirm the selectivity and reusability of chitosan-based adsorbents but also identify the practical challenges and costs associated with real-world implementation.
- (2) While chitosan has been recognized as a renewable and biodegradable material, there remains a lack of systematic assessments of its overall environmental footprint. To ensure its long-term sustainability and societal acceptance, it is critical to evaluate the life cycle, carbon footprint, and potential risks associated with both large-scale production and the end-of-life management of chitosan-based adsorbents. Field-based life cycle assessment (LCA) studies—covering raw material sourcing, manufacturing, operational performance, and regeneration or disposal—would provide robust data to guide policy and industry adoption. Such

assessments, carried out in tandem with pilot-scale experiments, offer a more realistic evaluation of the environmental trade-offs, thereby allowing for data-driven decision-making in technology scale-up.

- (3) Although laboratory studies have demonstrated chitosan's excellent adsorption capabilities, it is essential to confirm its performance in practical, full-scale settings. Pilot-scale and field investigations can reveal factors—such as competing ions, pH fluctuations, or flow rate variability—that may reduce adsorption efficiency under actual wastewater treatment conditions. These real-world validations will help identify current bottlenecks (e.g., operational stability regeneration challenges) and guide the development of cost-effective, scalable solutions for industry and municipal sectors.
- (4) Recent trends indicate decreasing academic interest in chitosan alongside a growing focus on biochar and other novel adsorbent materials. However, the existing body of work on chitosan demonstrates tangible advantages, including its natural abundance and biodegradable nature. Future research should therefore critically compare chitosan-based materials with emerging alternatives, emphasizing key metrics such as cost-effectiveness, resource availability, adsorptive capacity, and overall environmental benefits. In-field comparative pilot studies are particularly important for determining under which conditions chitosan-based systems can outperform—or synergistically complement—other adsorbents. Such data-driven comparisons will clarify where chitosan might still hold unique advantages and where hybrid or entirely new solutions may be more appropriate.
- (5) Current studies have already underscored chitosan's versatility; however, leveraging its stimuli-responsive properties represents a promising path for further innovation. By incorporating functional groups or nanomaterials, chitosan can be engineered to exhibit changes in physical properties—such as swelling behaviour or porosity—in response to specific triggers (e.g., adsorbate concentration gradients, temperature shifts, or mechanical stress). Beyond laboratory-scale testing, carefully designed field pilots that track the performance of these “smart materials” under fluctuating wastewater conditions will be crucial. Specifically, real-time monitoring systems (e.g., in-line sensors for temperature or contaminant concentration) could be installed to capture how well these adaptive chitosan-based materials respond to dynamic field conditions. This approach will elucidate the feasibility, reliability, and potential cost savings of responsive adsorption processes in practical treatment scenarios.

6. Conclusion

This bibliometric analysis provides a holistic assessment of the research landscape on chitosan-based materials for contaminant removal from water and wastewater. By examining 9711 publications from 1993 to 2024 in the WOS database, our study confirms the steady annual growth of this field and underscores its interdisciplinary nature, intertwining chemistry, materials science, and environmental engineering. While early work predominantly targeted metals, dyes, and pesticides, recent trends indicate expanding interest in tackling emerging contaminants such as pharmaceuticals, PPCPs and PFAS. Moreover, research has also expanded to innovative domains, including solar-driven water purification scaffolds and advanced composites (e.g., chitosan@graphene oxide, chitosan-based MIPs, photocatalytic chitosan hybrids, chitosan/clay, and chitosan/metal sulfides) to boost adsorption capacity and selectivity.

Despite these promising developments, significant challenges remain. Large-scale adoption requires improving chitosan extraction and processing methods to reduce environmental impacts, addressing regeneration and structural stability issues, and validating performance in complex real-world settings. Additionally, while ML methods have

been introduced to optimize synthesis routes and predict adsorption properties, this area is still in its infancy compared to more established adsorbents such as activated carbon or biochar. Future research should emphasize pilot-scale and field trials, cost-effectiveness, and the creation of “smart” or stimuli-responsive chitosan composites to enhance their practical applicability. Through these concerted efforts, chitosan-based materials can be propelled from laboratory-scale demonstrations to impactful, scalable innovations that mitigate a wide range of contaminants and safeguard global water resources.

Abbreviation

CAC	commercial activated carbons;
PFAS	poly- and perfluoroalkyl substances
PPCPs	pharmaceuticals and personal care products
PFOS	perfluorooctanesulfonic acid
PFOA	perfluorooctanoic acid
DFT	density functional theory
EDA	electron-donor-acceptor
pHpzc	zero charge pH
COF	covalent organic frameworks
MOF	metal-organic frameworks
MIPs	molecularly imprinted polymers
ANN	artificial neural networks
ML	machine learning; RF: random forest

CRedit authorship contribution statement

Chong Liu: Writing – review & editing, Writing – original draft.
Grégoire Crini: Writing – review & editing, Writing – original draft.
Eric Lichtfouse: Writing – review & editing, Writing – original draft.
Lee D. Wilson: Writing – review & editing, Writing – original draft.
Lorenzo A. Picos-Corrales: Writing – review & editing, Writing – original draft.
Paramasivan Balasubramanian: Writing – review & editing, Writing – original draft.
Fayong Li: Writing – review & editing, Writing – original draft.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jwpe.2025.107327>.

Data availability

Data will be made available on request.

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Supporting information

Text S1: Reviews _ Chitosan-based materials for contaminants removal (2022-2024)

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Text S2: Results and discussion of bibliometric analysis

1. Analysis of research trends

The annual number of publications and citation counts serve as crucial indicators reflecting the popularity of chitosan-based materials in water treatment. Figure 1 illustrates the annual number of publications and citation counts from 1993 to 2024, revealing an exponential growth in the number of papers published on chitosan-based materials in wastewater treatment over the past three decades. According to the number of publications, this study delineates three distinct phases. In Stage I (1993-1998), the annual number of publications was less than 10 papers, with citation counts averaging below 50. A review of relevant literature indicates that this phase primarily involved research on chitosan-based adsorbents for removing metal cations from water. Stage II (1999-2007), the annual publication below 100 papers, with citation counts below 2000. Notably, this phase expanded beyond removing metal cations to encompass the adsorption of inorganic anions and organic contaminants by chitosan-based adsorbents. Stage III (2008-2024) witnessed an explosive growth in both the number of published papers and citation counts. The number of publications peaked in 2021, reaching 982 articles. The citation counts remained stable in 2021 and 2023 but showed an upward trend in 2024, reaching approximately 58,086. The increasing number of publications and citations related to chitosan-based materials highlights the growing research interest in their potential applications as pollutant adsorbents, biofloculants, and photocatalytic oxidation matrices. It can be seen that the number of publications in 2022 and 2023 experienced a slight decrease compared to 2021, which could be potentially attributed to saturation in the relevant research field and the impact of the COVID-19 pandemic. However, given the heightened significance of global environmental concerns and the passing of the COVID-19 pandemic, research in related fields is anticipated to expand persistently after 2025. So, researchers must engage in comprehensive studies to develop cost-effective and environmentally friendly chitosan-based materials to remove contaminants in wastewater effectively.

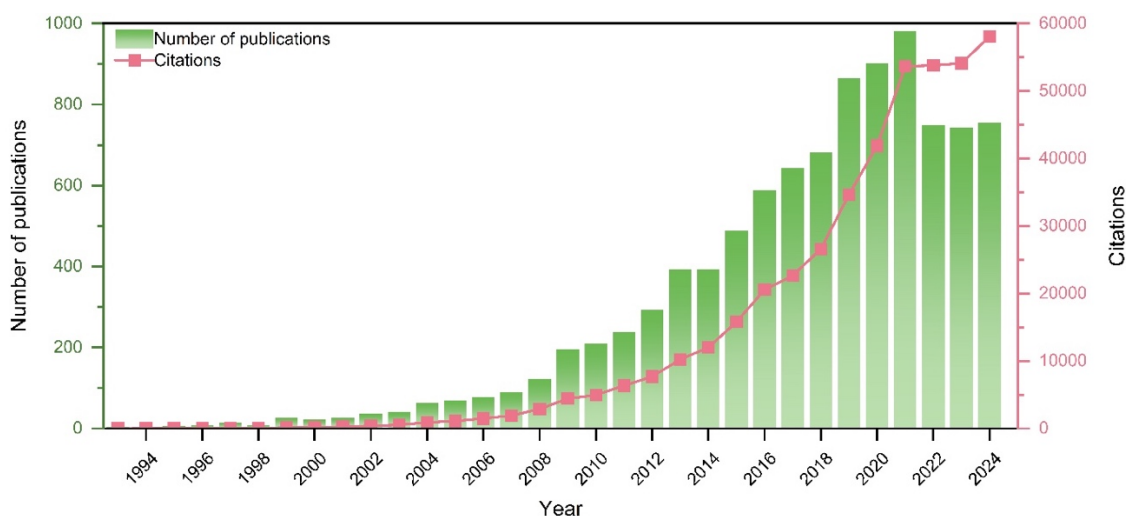


Figure 1. Annual publication number and citations during 1993—2024 on the use of chitosan-based materials for contaminant removal.

2. Key contributors and collaborative analysis

2.1 Contributions of countries

The research of chitosan-based materials for removing contaminants from wastewater has been extensively explored, with scholarly contributions from 110 countries. As delineated in Table 1, the top 10 countries regarding the number of published articles are provided. China is the preeminent country in this domain, having published 3,623 publications, constituting 35.95% of the aggregate. This voluminous output attests to China's substantial investment in scientific research within this field. Followed by China, India (1,270 articles), Iran (835 articles), Egypt (655 articles), and Brazil (533 articles) have also made

substantial contributions to the field. The H-index, which reflects researchers' academic productivity and impact, highlights China's prominent position at the forefront, boasting an impressive H-index of 164. It is noteworthy that, despite China's prolific publication output, the Average citation frequencies (ACF) for France (86.71) are surpassed by those of the USA (72.624), Saudi Arabia (57.42), and China (44.74). Centrality, indicative of collaborative intensity, designates the USA with the highest score of 0.20.

Table 1. Top 10 countries in terms of published papers from 1933 to 2024 on using chitosan-based materials for contaminant removal.

Rank	Country	Counts	Proportions (%)	Centrality	H-Index	ACF*
1	China	3,623	35.95	0.09	164	44.74
2	India	1,270	12.60	0.08	110	43.72
3	Iran	835	8.29	0.09	90	37.73
4	Egypt	655	6.50	0.03	75	34.91
5	Brazil	533	5.29	0.06	69	34.72
6	Malaysia	464	4.61	0.08	78	43.40
7	Saudi Arabia	407	4.04	0.12	84	57.42
8	USA	362	3.59	0.20	86	72.62
9	South Korea	293	3.11	0.01	70	49.93
10	France	292	2.91	0.05	73	86.71

ACF*: Average citation frequencies of each paper.

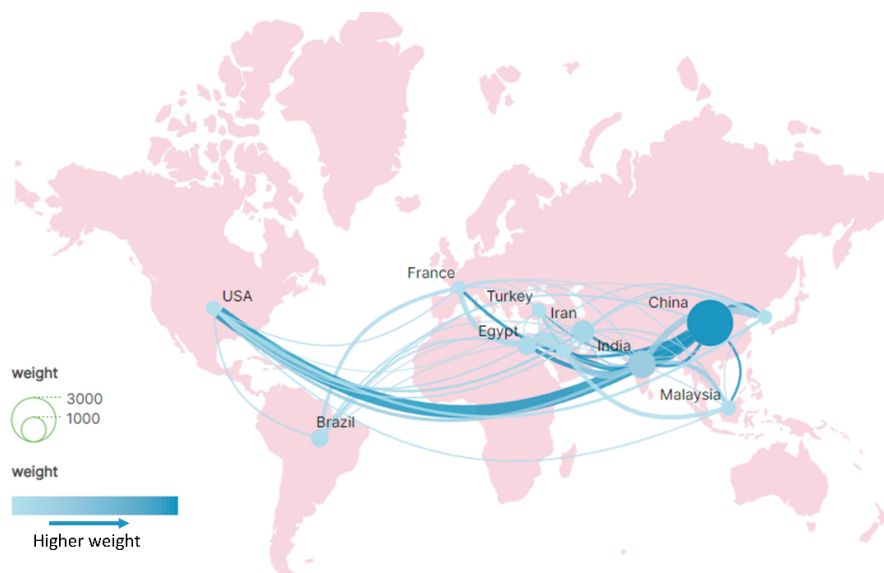


Figure 2. Global geographical distribution of papers and collaboration patterns using chitosan-based materials for contaminant removal.

2.2. Contributions of institutions

According to the statistical analyses conducted using VOSviewer and CiteSpace, 4684 institutions were identified to use chitosan-based materials to remove contaminants from wastewater. Notably, 712 of these institutions surpassed the threshold of a publication count of 5. Table 2 delineates the top 10 institutions in terms of published research output. The Chinese

Academy of Sciences, Islamic Azad University (Iran), and Universiti Sains Malaysia emerged as the most prolific contributors, with publication counts of 279, 215, and 170 articles, respectively. The Chinese Academy of Sciences and Islamic Azad University primarily focus on developing novel chitosan-based composite materials for removing metal cations and dyes from wastewater. Similarly, Universiti Sains Malaysia emphasizes developing chitosan-based composite materials to remove organic microcontaminants from water. Additionally, noteworthy contributions in this field are attributed to institutions such as King Saud University (95 articles), the Russian Academy of Sciences (85 articles), and Chongqing University (80 articles). Notably, among the top ten institutions by publication count, five commenced their research on chitosan-based adsorbents for wastewater treatment around 1998. Figure 3 illustrates the principal collaborative institutions and relationships in the relevant domain. The Chinese Academy of Sciences and Islamic Azad University occupy pivotal positions, having established extensive and profound collaborations with other domestic institutions within their respective countries.

Table 2. Top 10 institutions on the use of chitosan-based materials for contaminant removal.

Rank	Institution	Country	Counts	Centrality	YFP*
1	Chinese Academy of Sciences	China	279	0.17	2006
2	Islamic Azad University	Iran	215	0.05	2011
3	Universiti Sains Malaysia	Malaysia	170	0.01	1998
4	King Saud University	Saudi Arabia	138	0.08	2011
5	Russian Academy of Sciences	Russia	135	0.04	1999
6	Chongqing University	China	128	0.03	2017
7	National Research Centre	Egypt	122	0.01	1998
8	Tsinghua University	China	121	0.04	2009
9	Nuclear Materials Authority	Egypt	108	0.05	2015
10	École des Mines d'Alès	France	105	0.15	1998

YFP*: Year of first publication.

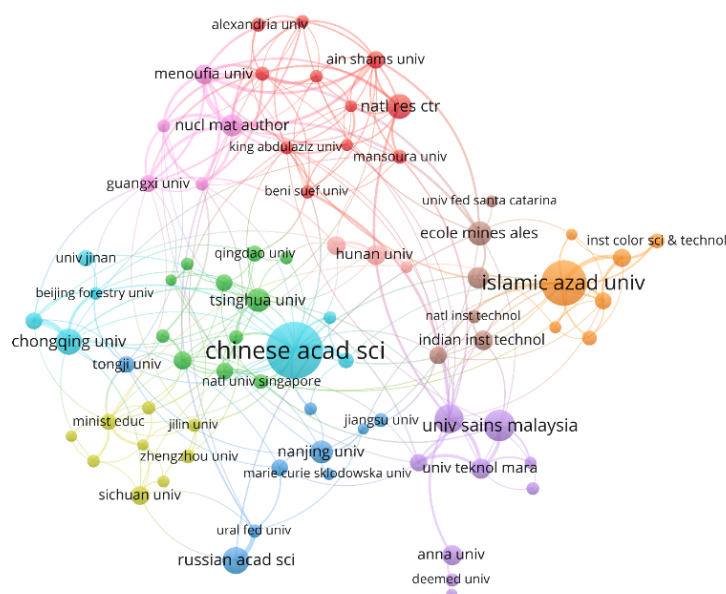


Figure 3. The cooperation network of the productive institutions on chitosan-based materials for contaminant removal.

2.3 Contributions of authors

Between 1993 and 2024, 23199 authors engaged in research on removing contaminants from wastewater using chitosan-based adsorbents, with 958 of them contributing more than 5 publications. The top 10 authors who have published more articles are presented in Table 3. Guibal E. from IMT Mines Alès, France, emerges as the most prolific author with 125 articles, followed by Sankaran M. from Gandhigram Rural Institute-Deemed University (95 articles) and Huaili Z. from Chongqing University (71 articles). Notably, the papers published by Guibal E. boast the highest H-index and ACF, achieving values of 58 and 85.36, respectively. Regarding primary research fields, most researchers employ chitosan-based adsorbents to eliminate metals and dyes from wastewater. Figure 4 illustrates the density map of cooperation among authors, with incremental yellow shades of color indicating more frequent collaboration. It is evident from the figure 4 that while some authors conducted independent research in this field, collaboration remains the prevailing trend.

Table 3. Top 10 authors on the use of chitosan-based materials for contaminant removal.

Name	Counts	Country	H-index	ACF*	MCT*
Guibal E.	126	France	58	85.36	metals; dyes; adsorption properties; mechanism
Sankaran M.	95	India	43	53.63	metals; synthesis
Huaili Z.	71	China	28	30.59	metals; adsorption properties
Luiz D.G.	61	Brazil	32	52.15	metals; dyes; adsorption properties
Aiqin W.	56	China	36	77.55	dyes; synthesis
Luiz P.	56	Brazil	33	52.59	dyes; adsorption properties
Viswanathan N.	52	India	27	50.48	metals; synthesis
George Z.K.	50	Greece	33	78.02	metals; dyes
Wilson L.D.	47	Canada	23	33.49	anions; metals; synthesis; mechanism
Urszula F.	43	Poland	13	13.12	anions; dye

MCT* : Most contributed topics; ACF* : Average citation frequency



Figure 4. Author collaboration density chart on the use of chitosan-based materials for contaminant removal.

2.4 Literature Categories and Source Analysis

2.4.1 Journal analysis

A total of 845 journals have published pertinent literature on the removal of contaminants from wastewater using adsorbents based on chitosan. Table 4 enumerates the top 10 journals with the highest number of publications in the relevant fields. These journals reflect the latest research trends in this domain and provide a platform for researchers to showcase their recent progress and findings. The journal with the most publications is the "*International Journal of Biological Macromolecules*," which has 781 articles (Impact Factor₂₀₂₃ = 7.7). Following are "*Desalination and Water Treatment*" (436 articles; Impact Factor₂₀₂₃ = 1.0), "*Chemical Engineering Journal*" (388 articles; Impact Factor₂₀₂₃ = 13.3), and "*Carbohydrate Polymers*" (348 articles; Impact Factor₂₀₂₃ = 11.2), among others. Notably, while the "*International Journal of Biological Macromolecules*" has the highest number of publications (Average Citation Frequency [ACF] = 45.5), the ACF is considerably lower than the 127.4 of the "*Journal of Hazardous Materials*" and 99.9 of the "*Chemical Engineering Journal*." In terms of the H-index, the highest is 111 for the "*Journal of Hazardous Materials*," indicating its substantial academic impact.

Table 4. Top 10 journals on the use of chitosan-based materials for contaminant removal.

Rank	Journal	Counts	H-Index	ACF*	IF ₂₀₂₃	JCR
1	International Journal of Biological Macromolecules	781	78	45.5	7.7	Q1
2	Desalination and Water Treatment	436	31	10.9	1.0	Q3
3	Chemical Engineering Journal	388	108	99.9	13.3	Q1
4	Carbohydrate Polymers	348	80	74.7	11.2	Q1
5	Journal of Hazardous Materials	320	111	127.4	12.2	Q1
6	Journal of Environmental Chemical Engineering	233	43	31.9	7.4	Q1

7	RSC Advances	205	44	34.9	2.9	Q2
8	Journal of Applied Polymer Science	191	38	27.6	2.7	Q2
9	Environmental Science and Pollution Research	187	29	18.9	-	Q1
10	Chemosphere	166	45	67.5	-	Q1

ACF*: Average citation frequencies of each paper.

2.4.2 Discipline analysis

Analyzing the research type using WOS and CiteSpace proves instrumental in fostering interdisciplinary collaborative development. Publications centered on the adsorption of contaminants in water by chitosan-based materials span 93 categories, with Figure 5 delineating the ten most prevalent categories. "Chemical Engineering" emerges as the predominant category, boasting the highest frequency (2163 counts), underscoring researchers' pronounced emphasis on engineering applications. The following are "Polymer Science," "Environmental Sciences", and " Environmental Engineering ". It is noteworthy that, despite a relatively moderate frequency of occurrence (504 counts), "Materials Science Multidisciplinary" exhibits the highest centrality (0.44), surpassing that of other disciplines. A majority of the top ten subjects align with the domains of chemistry ("Chemical Engineering, ""Chemistry Applied," "Chemistry Multidisciplinary," "Chemistry Physical") and the environment ("Environmental Sciences," " Environmental Engineering"). Notably, distinct intersections between these domains exist, especially in chemistry and the environment. In essence, the impact and collaboration across diverse disciplines significantly contribute to the research output in this domain, thereby advancing its development and progress.

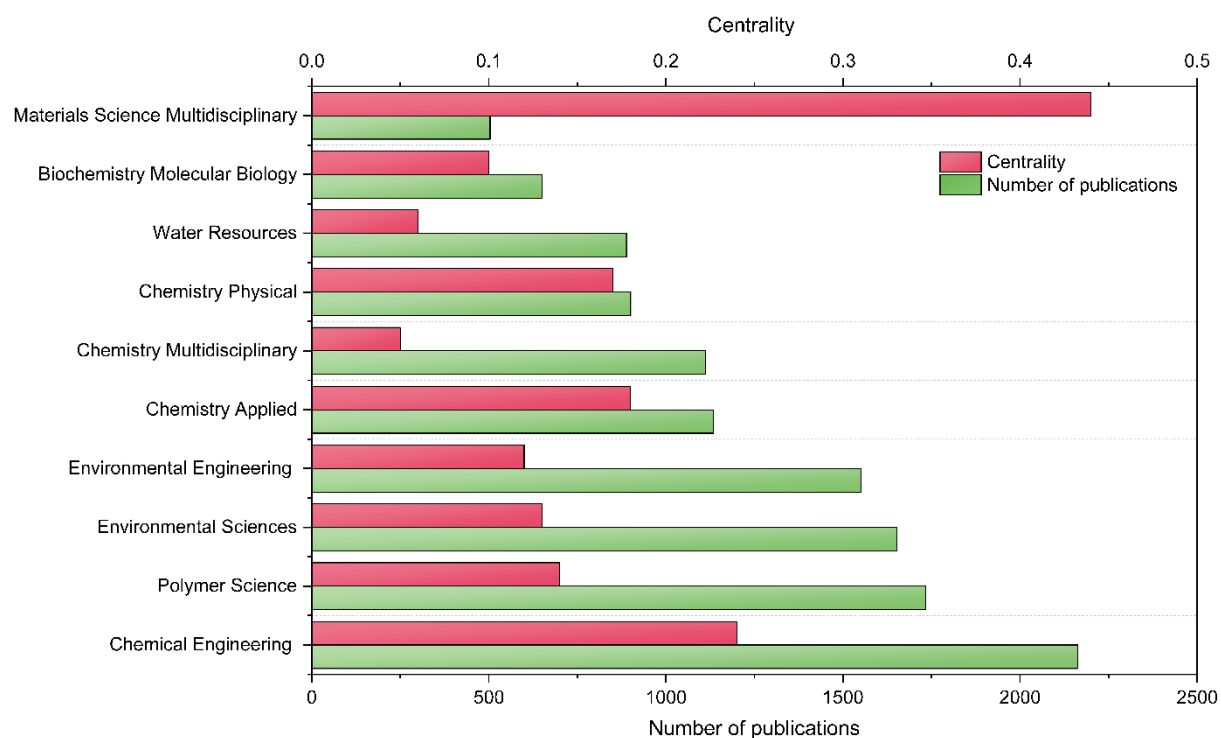


Figure 5. Top 10 disciplines on the use of chitosan-based materials for contaminant removal.

2.5 Knowledge base analysis

2.5.1. Crucial literatures

The burstness of an article refers to the degree to which the article receives a large amount of attention quickly. The burst index and total citations are vital indicators to measure the quality and importance of an article. Articles with higher burst index and

higher total citation frequency are representative of the field's literature and can significantly impact its development. The literature was selected using CiteSpace, and papers with a burst index exceeding 40 and a citation frequency surpassing 750 were included. A total of 8 papers met the conditions, and the results are shown in Table 5. As shown in Table 5, it can be seen that most of articles were published between 2011 and 2016, corresponding to Stage III, a phase characterized by the explosive growth of relevant research. Ranking by the number of citations, it is noteworthy that three of the top 4 are attributed to Crini G.'s team from the University of Franche-Comté, France, underscoring their outstanding contributions and leadership in this field.

Overall, all of the selected articles belong to the review category. Besides, most discuss removing metal ions and dyes with chitosan-based materials. In a notable review authored by Crini, which was published in "*Bioresource Technology*" and garnered the highest citation count of 5542, the study highlights the efficacy of low-cost natural sorbents as adsorbents, particularly emphasizing their exceptional capability for removing specific dyes [1]. Yagub et al. summarized dye removal adsorbents from wastewater, critically analyzing adsorption conditions and maximum adsorption capacity [2]. Crini and Badot worked on chitosan's adsorption mechanisms and reaction parameters as a low-cost biosorbent in batch studies for removing dyes from wastewater [3]. Similarly, Crini illustrated the developments in new modified polysaccharides for removing toxic compounds and showed the advantage of these biopolymers in wastewater treatment [4]. The review by Ngah et al., in "*Carbohydrate Polymers*," with the highest burst index of 100.95, discusses the applications of chitosan composite materials in removing dyes and metal ions over the past decade and exploring the associated adsorption mechanisms [5]. Guibal reviewed the mechanisms of chitosan-based adsorbents for metal ion adsorption and discussed the potential utilization of metal-loaded sorbents for various environmental applications [6]. Vakili et al. elaborated on the latest progress in removing dyes from wastewater using chitosan and its derivatives, which provides a new point for future research to address knowledge gaps in relevant areas [7]. Additionally, Zhang et al. reviewed the potential application of modified chitosan in adsorbing heavy metal ions and discussed related adsorption mechanisms and recycling of metal ions [8].

2.5.2 Keywords analysis

The frequency and centrality of keywords serve as crucial indicators within the analytical domain, delineating the research direction. Using CiteSpace and VOSviewer, the analysis revealed 10,761 keywords related to chitosan-based materials for removing water contaminants, with 912 appearing more than five times. It is worth noting that terms such as "aqueous solution," "removal," "adsorption," "chitosan," and "sorption" occur much more frequently than other keywords in this investigation. To avoid potential graph errors, the graph in this article excludes the abovementioned keywords, focusing on the other top 20 primary keywords. This study constructs a strategic coordinate map based on the average counts and centrality values of the top 20 keywords (883, 0.0385) as a reference point. This classification results in the segregation of keywords into distinct quadrants. The specific findings are illustrated in Figure 6.

In *Quadrant I*, keywords exhibit high frequency and centrality, akin to star products in the *Boston Matrix*. It can be explained that "equilibrium" and "kinetics" are the primary research processes in the removal of contaminants (e.g., "heavy metal") from "wastewater" using chitosan-based "adsorbents." Besides, "activated carbon" is frequently employed as a commercial adsorbent for comparative analysis with chitosan-based adsorbent. This is a prominent research topic in the current domain and is intricately linked to other research areas. In *Quadrant II*, keywords display low frequency and high centrality, primarily involving the "efficient removal" of contaminants such as "heavy metal ions (e.g., Cu(II))" and "methylene blue." In *Quadrant III*, keywords display low frequency and low centrality, mainly comprising "metal ion," "dye," "biosorption," "composite," "graphene oxide," "nanocomposite," and "bean." In *Quadrant IV*, keywords such as "ion" and "water" exhibit

high frequency and low centrality. Consistent with the above conclusion, the prevailing research focus in the water treatment domain using chitosan-based materials is on "heavy metal" and "dye" contaminants, with a secondary emphasis on analyzing adsorption mechanisms and synthesizing chitosan-based composite materials.

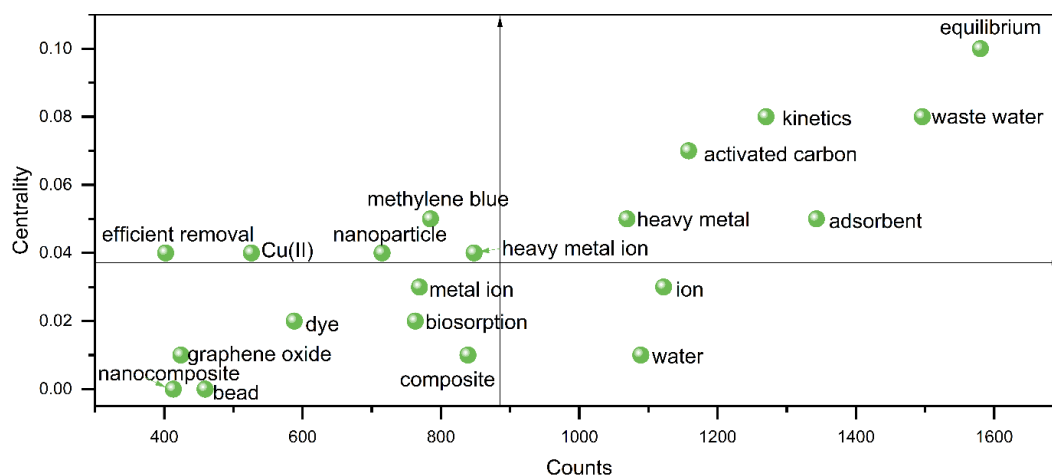


Figure 6. The graph of primary keyword frequency and centrality.

Organize these keywords chronologically based on their emergence, ranging by time, and present the findings in Table 6. The intensity of color in the squares within the figure 6 directly correlates with the degree of prominence, with the red square being the most burstness. As indicated in Table 6, research focal points in Stages I and II encompass the exploration of chitin, cadmium, resin, derivatives, chitosan beads, metals, reactive dyes, sorption, metal ions, acid dyes, adsorption isotherms, sorbents, separation, behavior, adsorption kinetics, and the development of low-cost adsorbents. These keywords exhibit characteristics of starting early and lasting long. Generally speaking, chitosan is mainly used to remove metal cations and dyes at this Stage. Keywords associated with Stage III emerged around 2014, with a notable surge commencing around 2017 (indicated by the black section). Stage III predominantly involves the synthesis of chitosan-based materials and other types of adsorbent material, including terms such as "graphene oxide," "carbon nanotube," "magnetic chitosan," and "fabrication." Additionally, it encompasses vocabulary related to the efficient removal of contaminants, such as "efficient removal," "adsorption property," and "selective adsorption." The keywords above continue at the burst stage, indicating their position as primary and actively investigated topics.

The CiteSpace software employs the Log-Likelihood Ratio algorithm for conducting cluster analysis on keywords ($Q = 0.8989 > 0.3$ and $S = 0.9654 > 0.7$ representing the reason and credibility of clustering), with Figure 7 illustrating the primary clusters. The adsorption isotherm elucidates the analyte's affinity, trends, and adsorption mechanism toward the adsorbent [9]. Furthermore, a comprehensive understanding of the adsorption kinetics is imperative for acquiring insights into the potential control step and the intricacies of the adsorption mechanism [9]. Cluster #0 sorption isotherms, #4 adsorption isotherms, #10 adsorption kinetics, and #14 Langmuir isotherms emerge as the largest cluster. These clusters delineate the mechanistic exploration of pollutant adsorption processes using chitosan-based materials. The investigation encompasses adsorption kinetics and thermodynamics to enhance adsorption efficiency and cost-effectiveness. Moreover, chitosan's outstanding functional groups, including amino and hydroxyl groups, render it an exceptional adsorbent for eliminating heavy metals and dyes from aqueous environments [4,9]. Cluster #1 reactive dye, #3 dye adsorption, and #8 concerning reactive black 5 pertain to using chitosan-based adsorbents for diverse dye adsorption in sewage. Cluster #5 heavy metals, #11 heavy metal ions, and #13 metal speciation correspond to exploring chitosan derivative adsorption behaviour concerning various toxic metals in aqueous solutions. Unmodified chitosan exhibits low stability, mechanical strength, and surface area in acidic conditions,

constraining its efficacy in pollutant removal [5,8]. #3 graphene oxide and #16 glutaraldehyde cross-linking primarily address modified chitosan. A variety of methods for chitosan modification are explored to enhance its pollutant removal efficiency.

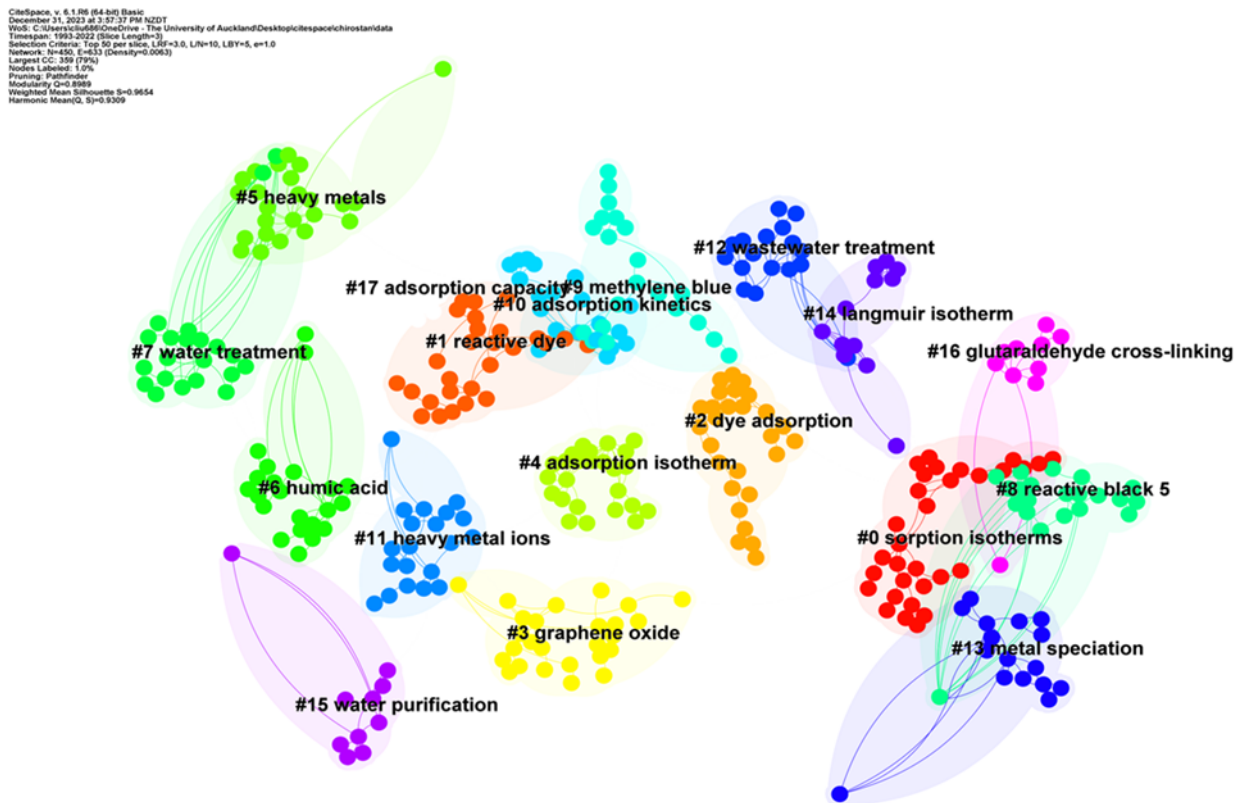


Figure 7. Cluster of keywords co-occurrence map.

Table 5. Representative articles about using chitosan-based materials for contaminant removal.

Rank	Citations	Burst	Title	Author	Source	Impact Factor	Year
1	5,542	43.47	Non-conventional low-cost adsorbents for dye removal: A review	Crini G.	Bioresource Technology	11.4	2006
2	4,105	41.41	Dye and its removal from aqueous solution by adsorption: A review	Yagub M.T.	Advances in Colloid and Interface Science	15.6	2014
3	2,811	77.58	Application of chitosan, a natural aminopolysaccharide, for dye removal from aqueous solutions by adsorption processes using batch studies: A review of recent literature	Crini G.	Progress in Polymer Science	27.1	2008
4	2,698	40.85	Recent developments in polysaccharide-based materials used as adsorbents in wastewater treatment	Crini G.	Progress in Polymer Science	27.1	2005
5	2,321	100.95	Adsorption of dyes and heavy metal ions by chitosan composites: A review	Ngah W.S.W.	Carbohydrate Polymers	11.2	2011
6	2,004	62.95	Interactions of metal ions with chitosan-based sorbents: a review	Guibal E.	Separation and Purification Technology	8.6	2004
7	1,044	82.26	Application of chitosan and its derivatives as adsorbents for dye removal from water and wastewater: A review	Vakili M.	Carbohydrate Polymers	11.2	2014
8	755	79.24	Removal of heavy metal ions using chitosan and modified chitosan: A review	Zhang L.	Journal of Molecular Liquids	6.0	2016

Table 6. Top 25 keywords exhibiting burstness in the utilization of chitosan-based materials for the removal of contaminants.

Keywords	Year	Strength	Begin	End	1993 - 2024
chitin	1994	56.84	1994	2013	
cadmium	1994	37.33	1994	2013	
resin	1994	27.32	1994	2013	
derivative	1996	35.3	1996	2013	
chitosan bead	1997	30.9	1997	2016	
metal	1997	26.71	1997	2010	
reactive dye	1997	64.7	1999	2016	
sorption	1994	50.07	1999	2013	
metal ion	1994	41.11	1999	2010	
acid dye	1999	40.18	1999	2013	
adsorption isotherm	2000	33.32	2000	2016	
sorbent	2000	28.61	2000	2016	
separation	1997	31.06	2002	2016	
behavior	2000	33.16	2005	2016	
adsorption kinetics	2005	23.06	2005	2013	
low cost adsorbent	2008	33	2008	2016	
efficient removal	2014	50.26	2017	2021	
graphene oxide	2014	39.03	2017	2021	
magnetic chitosan	2017	34.66	2017	2019	
Cd(II)	2017	33.45	2017	2019	
optimization	2017	29.88	2017	2021	
fabrication	2017	29.55	2017	2021	
carbon nanotube	2017	27.39	2017	2019	
adsorption property	2017	26.99	2017	2019	
selective adsorption	2017	23.92	2017	2021	

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