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Exploring the potential of chitosan-based biopolymers in advanced environmental applications: an overview

Explorando o potencial de biopolímeros à base de quitosana em aplicações ambientais avançadas: uma visão geral

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ABSTRACT

Chitosan, a biopolymer derived from chitin, boasts a broad spectrum of industrial and environmental applications. Owing to its porosity, amino and hydroxyl groups, and other inherent characteristics, this polymer presents a promising option for various applications, particularly in the adsorption of emerging pollutants and the fabrication of bioplastics and biosensors. However, chitosan faces limitations concerning polymer swelling, low mechanical strength, and solubility. These drawbacks can be overcome by incorporating composites into the chitosan matrix, thereby enhancing the overall strength of the polymer and expanding its environmental utility. Thus, this review explores the environmental applications of chitosan, mainly in pollutant removal from air, soil, and water, its utilization in bioplastics and biosensors, as well as an exploration of supplementary materials such as diatomaceous earth, zeolite, and bentonite, which, when combined with chitosan, exhibit remarkable efficacy in environmental decontamination.

Keywords: Adsorption; Biosensing techniques; Biotechnology; Conservation of natural resources; Environmental remediation; Green chemistry technology.

RESUMO

A quitosana, um biopolímero derivado da quitina, apresenta um amplo espectro de aplicações industriais e ambientais. Devido à sua porosidade, grupos amino e hidroxila e outras características intrínsecas, este polímero representa uma opção promissora para diversas aplicações, particularmente na adsorção de poluentes emergentes e na fabricação de bioplásticos e biossensores. No entanto, a quitosana possui limitações referentes ao inchaço do polímero, baixa resistência mecânica e solubilidade. Esses pontos fracos podem ser superados pela incorporação de compósitos na matriz de quitosana, reforçando a resistência global do polímero e ampliando sua utilidade ambiental. Assim, esta revisão explora as aplicações ambientais da quitosana, principalmente na remoção de poluentes do ar, solo e água, seu uso em bioplásticos e biossensores, bem como uma investigação de materiais suplementares como terra diatomácea, zeólita e bentonita, os quais, quando combinados com a quitosana, demonstram eficácia notável na descontaminação ambiental.

Palavras-chave: Adsorção; Técnicas biossensoriais; Biotecnologia; Conservação dos recursos naturais; Remediação ambiental; Química verde.

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Introduction

The constant advancement of the technological, industrial, agricultural, and urban sectors produces an increasing variety of pollutants in large quantities. These pollutants are often improperly disposed of in the environment, exposing populations and various life forms to contaminants. Such pollutants can cause harm to both health and the environment, necessitating the development of new, practical methods for their removal, remediation, replacement, and prevention of release or persistence in the environment (Boulaiche et al., 2019).

One approach to addressing this challenge is the utilization of biopolymers, with chitosan standing out due to its chemical and physical properties and environmental appeal. Chitosan is a natural, renewable, and cost-effective material that exhibits no toxicity to the environment or human or animal health (Ahmed et al., 2020; Peter et al., 2021). Moreover, it is recognized by the United States Environmental Protection Agency as a biodegradable polymer (Bakshi et al., 2020).

Consequently, the production of chitosan is extensively investigated across various scientific fields (Ahmed et al., 2020), gaining prominence, particularly in green chemistry, a field in growing demand and importance because it provides numerous essential, environmentally friendly products (Wang et al., 2021). Chitosan finds application in detecting heavy metal contamination, as a biosensor component, as a bioplastic substitute for certain conventional plastics, and in treating contaminated soil and water through contaminant adsorption processes (Sarode et al., 2019).

Despite its advantages, applications of chitosan may be constrained by its low solubility under biological conditions (Bakshi et al., 2020). This limitation can be mitigated by grafting new materials, forming composites, or chemically modifying its structure. In all these cases, enhancements in chemical properties and increased porosity of the biopolymer are achieved (El Knidri et al., 2018; Braz et al., 2020). Such improvements result in heightened adsorption capacity of chitosan without compromising its biocompatibility, mucoadhesiveness, or biodegradability traits (Pal et al., 2021).

Moreover, chitosan modification enables its application in various forms, such as nanofibers, membranes, hydrogels, powders, or solid forms (Ahmed and Ikram, 2016; Cho et al., 2021). In environmental processes, chitosan nanofibers are employed for metal ion removal, membranes for eliminating metals from aqueous solutions, hydrogels for heavy metal removal and immobilization of bioremediating enzymes, powders for removing heavy metals, dyes, and residual oil, and solid forms, such as flakes, for copper(II) and residual palm oil removal (Pal et al., 2021).

In this context, this review elucidates various applications of chitosan in the environmental field, focusing on novel materials that can augment the structural characteristics of this biopolymer. Additionally, it discusses sustainable alternatives for chitosan extraction/production (e.g., NADES and biological methods) and the potential of using pure chitosan and chitosan composites in emerging strategies for removing environmental pollutants and producing bioplastics and biosensors.

This review does not cover the entirety of the applications of chitosan-based composites in wastewater treatment and the adsorption mechanisms or their use as photocatalysts, which have been reviewed by Ahmed and Mohamed (2023). Other findings related to the use of chitosan and chitosan composites/nanocomposites in the adsorption of environmental pollutants from soil, water, and wastewater have been reviewed elsewhere (Pal et al., 2021; Musarurwa and Tavengwa, 2022; Issahaku et al., 2023). A scientometric analysis of chitosan reactions against chemical compounds and the use of chitosan-based biomaterials for biodiesel production have recently been reviewed by Prabakaran et al. (2024). The review published by El-Araby et al. (2024) may be consulted for information on chitosan physicochemical properties and the application of chitosan nanocomposites in the food, cosmetics, and pharmaceutical industries.

Literature search strategy

The literature survey and scientometric analysis were conducted using the Web of Science Core Collection database. The search was performed between January and March 2024 using combinations of the keywords: "chitosan", "biopolymer", "environmental applications", "water treatment", "soil remediation", "biosensors", "bioplastics", "air treatment", and "adsorption". "AND" and "OR" were applied to refine the search strategy.

Only peer-reviewed articles published in English were considered. The search primarily included studies published between 2010 and 2024, with the inclusion of older references when considered highly relevant to the historical and conceptual development of the topic. Review articles, original research papers, and highly cited studies related to environmental applications of chitosan were included.

The scientometric data were obtained directly from the Web of Science database using filters related to publication year, research area, document type, and keyword occurrence. Duplicate studies, articles unrelated to environmental applications, and publications lacking sufficient methodological information were excluded from the analysis.

Chitosan

Chitosan is an aminopolysaccharide obtained from chitin through either alkaline deacetylation or enzymatic deacetylation mediated by chitin deacetylase. Chitin is a natural polysaccharide composed of N-acetylglucosamine monomeric units linked by β-(1,4) glycosidic bonds, whereas chitosan consists predominantly of β-(1,4)-linked 2-amino-D-glucose monomeric units together with residual N-acetylglucosamine units resulting from incomplete deacetylation. Therefore, chitosan is considered a copolymer because it contains varying proportions of glucosamine and N-acetylglucosamine monomeric units within the same polymer chain (Moreno et al., 2018; Peter et al., 2021). It is notably recognized as the sole alkaline polysaccharide found in nature (Peter et al., 2021). This aminopolysaccharide exhibits cationic properties in acidic solutions, thereby imparting crucial attributes concerning solubility and ion exchange (Moreno et al., 2018; Peter et al., 2021). The physicochemical characteristics of this biopolymer are directly influenced by factors such as molecular weight, degree of crystallinity, free amino groups, extent of ionization, and degree of deacetylation, with the amino groups playing a pivotal role in determining the physicochemical properties and structural distinctions due to their involvement in intra- and intermolecular hydrogen bonding (Peter et al., 2021).

The structure of this polysaccharide is distinguished by linear β-(1,4) glycosidic bonds linking glucosamine and residual N-acetylglucosamine units along the polymer chain (Peter et al., 2021). Various living organisms biosynthesize chitosan, and it can be sourced from the exoskeletons of marine arthropods (such as shrimps and crabs) (Mohan et al., 2021; Shyam et al., 2021), insect cuticles (Lucas et al., 2021), and fungal cell walls (Lin et al., 2017). As a commercially extracted resource, chitosan is predominantly derived from the exoskeletons of marine arthropods, serving as a renewable reservoir of biopolymer (Bakshi et al., 2020). Figure 1 illustrates the primary sources of chitin extraction and delineates the alkaline deacetylation process.

Chitosan extraction: traditional and green solvents

The initial step in obtaining chitosan involves deproteinization and demineralization of a matrix (shrimp shells, fungi, or others) to extract chitin. Applying the deproteinization process before demineralization can optimize chitin yield. This sequence of processes enables control over excessive foam formation resulting from CO_2 release (Hisham et al., 2021). Proteins are eliminated using a dilute sodium hydroxide solution (ranging from 1 to 10%). In turn, mineral removal occurs using hydrochloric acid at room temperature to dissolve calcium carbonate and release carbon dioxide. Following chitin extraction, chitosan can be obtained with varying degrees of deacetylation by once again controlling parameters such as alkaline concentration (40–60% NaOH), time, and temperature in an oxygen-free environment (Yijing et al., 2020; Hisham et al., 2021). Conditions such as temperature, reagent type, reaction time, and reagent concentration can impact chitosan's structure and final composition.

The chemical method is the most widely used for chitin extraction and chitosan production. This approach eliminates mineral salts such as calcium phosphate or carbonate, commonly found in chitin and chitosan. Acids, including nitric acid (HNO_3), sulfuric acid (H_2SO_4), hydrochloric acid (HCl), formic acid (HCOOH), and acetic acid (CH_3COOH), are commonly utilized to remove these salts. Subsequently, proteins are separated through an alkaline treatment with sodium hydroxide (NaOH). Industrial production commonly uses

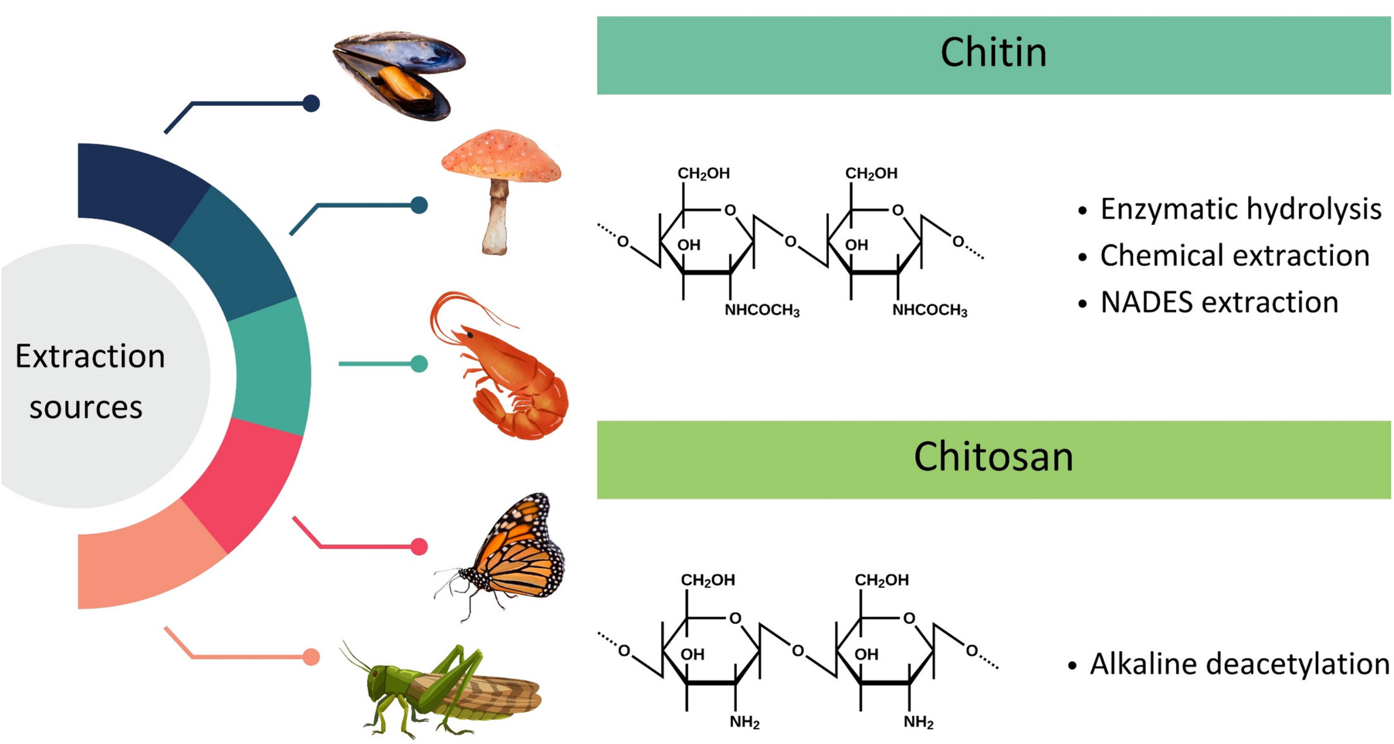

Figure 1 – Sources of chitin (marine arthropods, fungi, insects), extraction processes (chemical and biological), and formation of chitosan by alkaline deacetylation of chitin

HCl, NaOH, and hydrogen peroxide (H_2O_2) to purify and treat chitin and chitosan polymers (Zainol Abidin et al., 2020).

Despite being considered economically viable, these methods can pose environmental challenges when applied on an industrial scale. The extraction process demands substantial energy consumption, leading to significant water wastage and generating aggressive acid-base effluents. Additionally, the reagents utilized can influence the properties of the extracted chitin. Consequently, compounds from green chemistry and enzymatic hydrolysis have gained traction in polymer extraction. These methods involve using environmentally safe solvents and enzymes, producing satisfactory chitin and chitosan yields (Ibitoye et al., 2018; Nuc and Dobrzycka-Krahel, 2021).

New biological techniques for chitin extraction from seafood waste have been developed, offering reduced processing costs, minimal degradation, and ecological viability (resulting in decreased waste production) (Peter et al., 2021). Enzymatic hydrolysis, utilizing chitinolytic enzymes obtained from *Chitinolyticbacter meiyuanensis* SYBC-H1, in conjunction with pretreatments that enhance chitin solubility and reduce crystallinity, has emerged as an alternative method. These pretreatments include milling, ultrasonic baths, supercritical fluids, deep eutectic solvents (DES), high-pressure homogenization, steam explosion, ionic liquids, and the use of fermentative bacteria (Wang et al., 2021; Zhou et al., 2021).

An environmentally friendly approach to chitin extraction involves DES. These solvents consist of liquid mixtures comprising pairs of hydrogen bond donors and acceptors. DES are considered greener solvents than conventional organic solvents, as their preparation primarily involves natural compounds or less hazardous chemicals. Modifying hydrogen bond donors and acceptors can adjust freezing properties, density, viscosity, and conductivity for each extraction or desired process (Morgan et al., 2021). In the realm of biopolymers, DES have been studied for starch (Zdanowicz et al., 2019), cellulose, lignin (Li et al., 2021a), and chitin dissolution. For chitin extraction, DES formulations containing choline chloride, zinc chloride, ferric chloride hexahydrate, and betaine hydrochloride have been utilized (Hong et al., 2020).

Another set of solvents, known as Natural Deep Eutectic Solvents (NADES), offers a greener alternative. NADES are formed by mixing two or more primary metabolites, which transform into a liquid at room temperature. These solvents offer advantages such as recoverability, reusability, and short extraction times. NADES, which comprise solely natural compounds, exhibit superior extraction properties compared to DES (Huang et al., 2018; Nuc and Dobrzycka-Krahel, 2021).

NADES possess robust hydrogen bonds that lower the melting temperature of the original components. Choline chloride is commonly used as a hydrogen bond acceptor, with urea, carboxylic acids (such as lactic and citric acid), and polyols serving as common donors (Smirnov et al., 2020). Combining these donors and acceptors generates a transparent, viscous liquid with a low melting point at room temperature and negligible vapor pressure. These biodegradable solvents offer a promising avenue for developing green processes (Pontillo et al., 2021).

Chitosan studies and global market

In recent years, studies on chitosan have grown significantly, ranging from improving extraction processes to exploring potential applications in various research fields, such as chemistry, polymer science, materials science, biochemistry, molecular biology, engineering, and environmental sciences (Web of Science Database, 2024).

The number of indexed articles investigating chitosan and published in scientific journals between 2017 and 2023 (Web of Science Database, 2024) increased by 55.76% during this period, with a total of 66,888 publications over seven years. The year 2023 had the highest number of publications on the subject, followed by 2022 and 2021, demonstrating a growing trend. This surge in research activity around this polymer has piqued the interest of various scientific disciplines.

Interest in chitosan for environmental applications, both within the global market and the scientific community, arises from its remarkable capacity to adsorb contaminants, its affinity for heavy metals, its ease of physical and chemical modifications, its applicability at high temperatures, its resistance to microbiological degradation, and the presence of amino groups (NH_2), coupled with its non-toxicity and biodegradability (Peter et al., 2021). Additionally, within the environmental domain, primary areas of study encompass the synthesis of nanocatalysts, water treatment focusing on the removal of heavy metal ions (e.g., Ag(I), Cr(VI), Cu(II), Cd(II), Pb(II), Hg(II), Zn(II), As, Au), dyes (Nasrollahzadeh et al., 2021), and micropollutants (including drugs, microplastics, industrial additives, and pesticides) (Cho et al., 2021; Sun et al., 2021).

Regarding the global market, according to the ReportLinker market report (ReportLinker, 2021), chitosan production is projected to reach approximately 281.7 thousand metric tons by 2027. Notably, chitosan is anticipated to demonstrate a CAGR of 16.9% (173.9 thousand tons). Noteworthy contributors to this market include the United States (31.6 thousand tons), China (48.5 thousand tons, with a 14.1% CAGR), Japan (13.3% CAGR), Canada (12.5%), and Germany (10.6% CAGR). China, being among the fastest growing in this cluster of regional markets, is also the country with the highest volume of studies and technological advancements in chitosan, with 11,952 articles and 64,116 patents registered between 2017 and 2021 (Web of Science Database, 2024), as shown in Figure 2.

According to the Global Chitosan Market Research Report, 2020–2026 (Market Data Forecast, 2022a), the chitosan market size in 2020 amounted to $10.21 billion, with an estimated 8.2% increase, reaching $11.2 billion by 2026. This represents a significant market presence, particularly when compared to graphene, a material also applicable in contaminant adsorption and biosensor structures, with its market val-

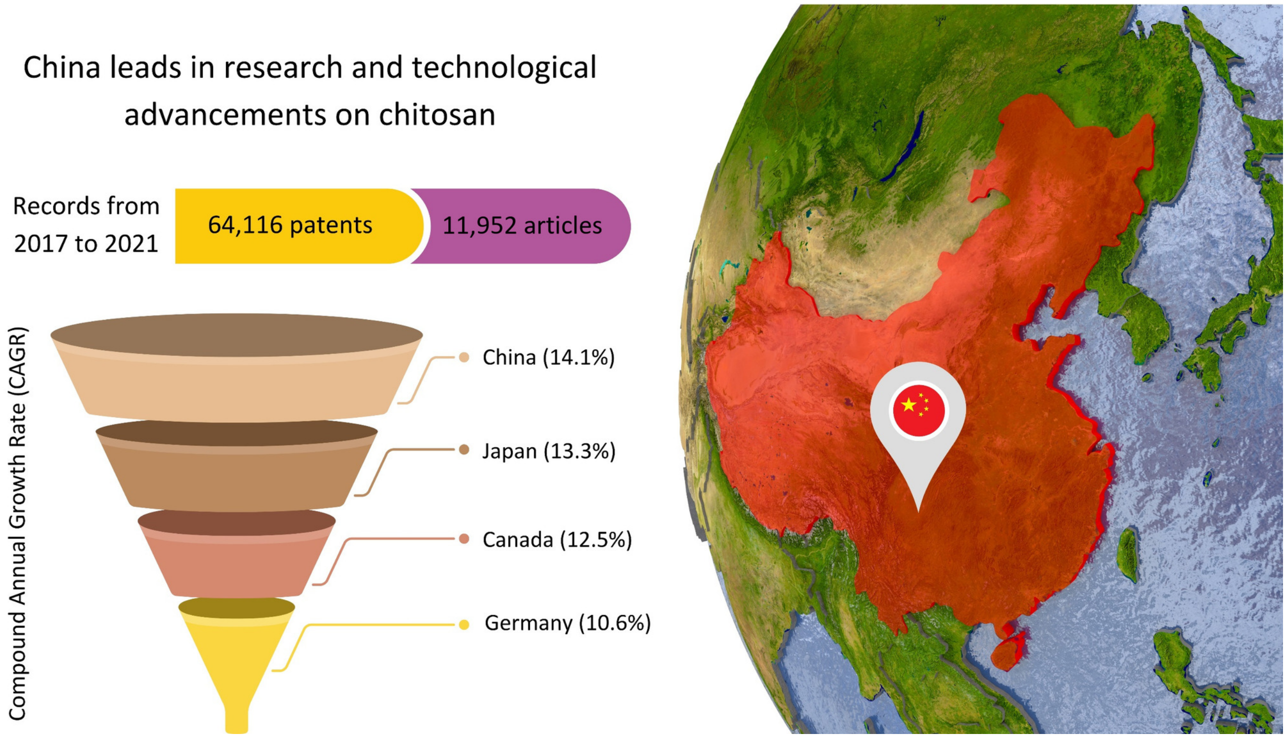

Figure 2 – Global market status of chitosan

ued at $117.34 million in 2021 and projected to reach $221.4 million by 2026 (Market Data Forecast, 2022b).

Environmental applications of chitosan

Chitosan stands out as a promising candidate for environmental applications. This biopolymer exhibits resistance to microbial degradation and possesses abundant amino and hydroxyl groups. Furthermore, its physical and chemical characteristics are easily modifiable, endowing the polymer with a high capacity for adsorbing contaminants (Musarurwa and Tavengwa, 2020). Its non-toxic, biodegradable nature and low production costs further enhance its appeal. The structure of chitosan facilitates interactions with cells, molecules, proteins, and other living organisms, which are crucial for its efficacy in environmental processes (Shariatinia, 2019). Moreover, chitosan possesses significant selective chelation properties, rendering it promising for heavy metal removal (Ardila et al., 2017).

This section will explore various studies (Table 1) demonstrating the efficacy of chitosan in composites for environmental applications, particularly in the production of bioplastics, the composition of biosensors, and the purification of air, soil, and water.

Bioplastic

The extensive use of conventional fossil-based plastics has contributed significantly to environmental pollution due to their low biodegradability and limited recycling potential, highlighting the need for more sustainable alternatives (Narancic and O'Connor, 2019; Taha et al., 2022).

In this context, the development of biodegradable membranes to replace conventional plastics has emerged as a promising strategy for promoting environmental sustainability (Taha et al., 2022). Chitosan has attracted considerable attention as an alternative to conventional plastics because it can be produced through environmentally friendly processes and possesses biodegradable, antimicrobial, and antioxidant properties. Its applications in plastic materials include the production of biodegradable plastics based on tapioca, N-isopropyl acrylamide, and chitosan (Syaubari et al., 2018); functional nanocellulose nanocomposites with alginate and chitosan for active food packaging (Lavrič et al., 2021); films produced from chitosan and cellulose extracted from pineapple leaves (Amalia et al., 2019); chitosan-based nanocomposite films and coatings (Kumar et al., 2020); and chitosan acetate films (Walzl et al., 2020). However, its most important application is in the food packaging industry, where it enhances the preservation of various food products, offers complete biodegradability, and represents an important strategy for reducing plastic pollution (Yanat and Schroën, 2021).

The biodegradation of chitosan is a key aspect of its environmental profile, as this biopolymer is degraded into amino sugars through physical, chemical, or enzymatic hydrolysis. Biochemically, chitosan depolymerization is mediated by lysozymes and chitosanases, such as those secreted by *Bacillus species* (Bakshi et al., 2020). The rate and

Table 1 – Summary of scientific studies using chitosan in environmental applications

Environmental field	Primary application	Chitosan properties leveraged	Prominent composites	References
Bioplastics	Replacement of conventional synthetic packaging	Biodegradability, antimicrobial and antioxidant properties, oxygen barrier	Chitosan/LDPE/MA/TBPB; PLA/Chitosan; Chitosan/Essential Oil	Kusumastuti et al. (2020); Chang et al. (2021); Tan et al. (2021); He et al. (2022)
Biosensors	Detection of pollutants (heavy metals, pesticides, phenols)	Gel-forming capacity, biocompatibility, efficient enzyme immobilization	AChE/CS/Fe_3O_4; AgNWs/HPMC/CS/Urease; Laccase/CS/Phthalocyanine	Rodrigues et al. (2018); Salvo-Comino et al. (2020a); Saenchoopa et al. (2021)
Air treatment	Filtration of bioaerosols and organic gases	Polar functional groups, antimicrobial activity, particulate retention	Chitosan aerogel/cellulose; Chitosan/nanosilver/TiO_2; Chitosan/PLA nanofibers	Li et al. (2018); Liu et al. (2019); Hsu et al. (2021); Zhang et al. (2021)
Soil treatment	Remediation and immobilization of toxic elements (Cr, Ni)	High adsorption selectivity, stabilization mechanisms, nutrient uptake enhancement	Chitosan/Biochar; Chitosan/Zeolite; Chitosan/Manganese dioxide; Chitosan/Bentonite	Najafi et al. (2021); Tanzeem-Ul-haq et al. (2021)
Water treatment	Adsorption of heavy metals, dyes, and pharmaceutical residues	Amino/hydroxyl group density, high surface area, ion exchange, porosity	Chitosan/Zeolite; Chitosan/Diatomaceous earth; Chitosan/Alkyl; Magnetic Chitosan	Salih et al. (2019); Janesch et al. (2020); Palacio et al. (2020); Coleman et al. (2021)

Note: AChE: Acetylcholinesterase; AgNWs: Silver nanowires; CS: Chitosan; HPMC: hydroxypropylmethylcellulose; LDPE: Low-density polyethylene; MA: Maleic anhydride; PLA: Polylactic acid; TBPB: tert-butyl peroxybenzoate; Cr: Chromium; Ni: Nickel.

extent of this process are influenced by the polymer's structural characteristics, particularly its molecular weight and degree of deacetylation. Adjusting these parameters modifies the susceptibility of the polymer chain to enzymatic cleavage, thereby allowing control over the degradation rate (El-Araby et al., 2024).

Recent studies consistently demonstrate that incorporating chitosan into polymeric matrices improves both the environmental and functional performance of bioplastics. Kusumastuti et al. (2020) incorporated 40% chitosan into low-density polyethylene (LDPE), resulting in increased tensile strength, a lower melting temperature, and approximately 100-fold greater biodegradability than LDPE alone. Similarly, Chang et al. (2021) developed PLA/chitosan films that exhibited more than 95% antimicrobial activity against *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas fluorescens*, extending the shelf life of grouper fillets by up to nine days. Likewise, Tan et al. (2021) demonstrated that chitosan films containing *Chrysanthemum morifolium* essential oil combined suitable physicochemical properties with antimicrobial and antioxidant activities, extending beef preservation by five days compared with conventional packaging.

Overall, chitosan exhibits desirable properties for composite materials intended for bioplastic production. Recognized as safe for food packaging applications by the Food and Drug Administration (FDA), chitosan stands out for its antimicrobial activity, which contributes to food preservation, as well as its film-forming ability, excellent oxygen barrier properties, and high mechanical strength. Furthermore, its incorporation into composite materials containing non-biodegradable plastic polymers can accelerate their degradation. However, it does not result in complete polymer degradation. Nevertheless, this represents a significant improvement compared with conventional plastics used alone (Kusumastuti et al., 2020; He et al., 2022). These recent studies, along with their respective formulations, applications, and main advantages, are summarized in Table 2.

Table 2 – Summary of recent studies on chitosan-based composite bioplastics and their environmental performance

Composite formulation	Target application	Key advantages and observations	References
Chitosan (40%) + LDPE + MA + TBPB	Bioplastic polymer blend	Reduced melting point; 100-fold increase in biodegradability compared to pure LDPE	Kusumastuti et al. (2020)
Chitosan (0.5%) + PLA (2%)	Fish fillet packaging	>95% antimicrobial efficacy against *E. coli* and *S. aureus*; extended shelf life	Chang et al. (2021)
Chitosan + *C. morifolium* essential oil	Beef and chicken packaging	Improved water vapor permeability; potent antioxidant action; extended preservation	Tan et al. (2021)
Chitosan/ZnO composite	Active film packaging	Accelerated biodegradation rates compared to synthetic plastics	He et al. (2022)

Note: LDPE: Low-density polyethylene; MA: Maleic anhydride; TBPB: tert-butyl peroxybenzoate; PLA: Polylactic acid; ZnO: Zinc oxide; *E. coli*: *Escherichia coli*; *S. aureus*: *Staphylococcus aureus*; *C. morifolium*: *Chrysanthemum morifolium*.

Biosensor

Biosensors play a pivotal role in environmental monitoring by facilitating the detection of pollutants, pathogens, and potentially toxic elements, as well as enabling the biological diagnosis of contamination by heavy metals and pesticides (Justino et al., 2017; Lukyanenko et al., 2019). Traditionally, diagnosing and monitoring biological contaminants entail chromatographic analysis, necessitating expensive equipment, pre-analytical steps, and reagents. Consequently, biosensors offer an economical alternative characterized by enhanced accuracy, ease of operation, and rapid contamination diagnosis compared to conventional methods (Justino et al., 2017).

These systems are crucial tools for swiftly and sensitively detecting pollutants (Cui et al., 2019). For instance, electrochemical biosensors are used to detect the phenolic compound catechol, which is extensively employed in pesticide formulations. Effective detection of this compound requires a suitable immobilization surface, for which chitosan proves instrumental. Furthermore, incorporating composites into chitosan's structure enhances its performance in biosensors utilizing the layer-by-layer (LbL) technique, ensuring the immobilization of enzymes within the polymer structure without compromising their functionality (Brett, 2018; Salvo-Comino et al., 2020a).

Biosensors comprise receptors, known as biological recognition elements (BREs), and transducers. Receptors recognize biological samples, while transducers translate the signal from the biological receptor into a chemical or physical signal, such as electrical, optical, or thermal signals. The choice of material for coupling with BREs is crucial, as it imparts additional physicochemical properties to the recognition system, thereby facilitating more accurate detection. Once again, chitosan emerges as a standout material due to its polymeric characteristics, gel-forming capacity, high surface/volume ratio, reusability, and environmental stability, making it an ideal candidate for preparing and immobilizing BREs (Jiang and Wu, 2019).

Salvo-Comino et al. (2020b) elucidated the use of chitosan supplemented with sulfonic copper phthalocyanine and gold nanoparticles for immobilizing laccase and tyrosinase enzymes, both phenoloxidases, using the LbL technique. This composite exhibited effective results for enzyme immobilization, fostering intimate material contact, efficient charge transmission, increased availability of detection sites, and enhanced material porosity and roughness.

Another notable application of chitosan as a fixation surface for pollutant detection was demonstrated by Saenchoopa et al. (2021). They coated screen-printed carbon electrodes with chitosan, urease, silver nanowires, and hydroxypropylmethylcellulose (AgNWs/HPMC/CS/Urease) to detect Hg(II) in water. This composite displayed increased sensor sensitivity, excellent Hg(II) detection performance, prolonged durability (1 month), functionality at room temperature, and optimal conductivity levels. Additionally, the composite exhibited outstanding recovery rates in drinking water (101.62–105.26%), establishing it as a practical, portable, low-cost, and viable material for heavy metal detection in field measurements.

In another study, Rodrigues et al. (2018) devised a biosensor with acetylcholinesterase (AChE) enzyme immobilized on a chitosan surface and magnetic iron nanoparticles (AChE/CS/Fe_3O_4) for the acetylcholinesterase-based detection of organophosphate pesticides. This sensor proved to be viable, with detection and quantification limits of 0.3 and 0.8 nmol/L, respectively, and recovery values of 108.3% for lake water samples. Hence, the proposed sensor offers a linear response, low detection limit, renewability, cost-effectiveness, and sensitivity to the targeted insecticide, making it a promising tool for pesticide detection.

Air purification

The issue of air pollution and its treatment, which is often inefficient, can significantly impact human and animal health. Hence, the development of multifunctional filters becomes imperative to eliminate various pollutants present in the air. Bioaerosols (such as bacteria, viruses, and fungi) and organic gases pose significant risks among air contaminants. In this context, nanotechnology-based materials show promise for creating filters with enhanced capacity for degrading and retaining micropollutants, thereby contributing to cleaner and safer air (Ahmed et al., 2020). Chitosan is a compelling material for developing such filters due to the polar functional groups on its outer surface and its notable antimicrobial activity, which make it an ideal candidate for capturing various micropollutants (Liu et al., 2019).

Despite the limited number of articles focusing on chitosan applications for air purification, existing studies demonstrate its feasibility and potential relevance, potentially stimulating further research in this area. Some studies highlight the preparation of chitosan aerogel spheres supported by microfibrillated cellulose for formaldehyde adsorption in indoor air purification (Zhang et al., 2021). Additionally, membranes composed of chitosan nanoparticles exhibit antimicrobial and air-filtering capabilities (Li et al., 2018), while chitosan, in combination with nanosilver and TiO_2, facilitates air disinfection in hospital wards (Liu et al., 2019).

To underscore the potential of chitosan as a filter, Hsu et al. (2021) demonstrated its efficacy in removing bioaerosols containing *E. coli* and *Bacillus subtilis* bacteria. Incorporating chitosan into polypropylene fibrous filters led to improved aerosol removal, with the chitosan-incorporated filter reducing bacterial survival rates compared to the control filter (without chitosan). When implemented in a natural indoor environment, the chitosan filter removed 80% of aerosols within 3 hours, showcasing its efficiency in antimicrobial filtration through a simple methodology of augmenting existing filters.

Li et al. (2018) utilized a filter based on polylactic acid (PLA) supplemented with chitosan through the electrospinning technique. This hybrid filter exhibited a highly porous structure with evenly distributed chitosan nanoparticles, resulting in exceptional filtration rates and antimicrobial activity against *E. coli* and *S. aureus*.

In another study, Liu et al. (2019) developed a reusable, fibrous, chitosan-based bilayer filter incorporating polymethylmethacrylate and polydimethylsiloxane fibers. This filter demonstrated remarkable particulate matter retention efficiency and antimicrobial activity, showcasing its potential for air purification and microorganism prevention.

Overall, chitosan emerges as a viable and efficient polymer for air purification, promoting health and environmental quality by curbing the proliferation of microorganisms in the air and thus minimizing the prevalence of particulate-contaminated environments.

Treatment of contaminated soils

Soil pollution resulting from industrial development, the escalating use of chemicals, and waste generated from mining, smelting, industry, and traffic poses significant environmental risks. Additionally, agriculture contributes substantially to soil contamination due to the increasing use of pesticides and fertilizers. These sectors collectively contribute to the accumulation of elements such as Cu, Cr, Zn, Pb, Sb, Hg, Co, Ni, Cd, and As, which, in high concentrations, can be detrimental to plants, animals, and human health (Pecina et al., 2021).

Chitosan has been employed in various applications, including soil stabilization research (Hataf et al., 2018), soil amendment using nanofungal chitosan for heavy metal adsorption (Alsharari et al., 2018), and the use of polyacrylamide and chitosan for flocculation and reduction of soil turbidity (Kang and McLaughlin, 2020).

In response to environmental concerns and the impact of soil pollution on plants, Najafi et al. (2021) investigated the toxic effects of chromium (Cr) on the growth of marigolds (*Calendula officinalis*). The study evaluated formulations of pure chitosan, biochar, zeolite, and manganese dioxide, as well as chitosan-based composites such as chitosan-biochar, chitosan-zeolite, and chitosan-manganese dioxide, as potential Cr adsorbents at concentrations of 0, 20, 60, and 180 mg/kg. The findings revealed that Cr in the soil directly affects the absorption of essential nutrients like P, K, and Fe by marigolds. Depending on the chemical form of Cr and its concentration, this element can pose risks to human or animal health through the consumption of contaminated plants. The use of polymers to mitigate these effects showed promise, as all chitosan-based composites demonstrated the ability to adsorb Cr and prevent its toxic effects on marigolds. The chitosan-manganese dioxide composite, at a concentration of 0.5% w/w, exhibited the highest efficiency, reducing Cr concentration in marigold aerial parts by 87.61%. Furthermore, the presence of chitosan-manganese dioxide led to significant increases in the dry mass and height of the plant, along with substantial enhancements in essential element concentrations (100% for P, 129.62% for K, and 320.33% for Fe). Thus, chitosan-manganese dioxide showed effective Cr stabilization properties and superior efficiency in removing toxic particles from the soil.

Another study by Tanzeem-Ul-haq et al. (2021) proposed a method to mitigate the toxic effects of nickel (Ni) on plants and remove Ni from soil to enhance lentil production conditions. The study utilized chitosan (CN), bentonite (BE), and biochar (BR) to immobilize Ni, resulting in improved plant growth conditions. The application of BE+CN and BR+CN composites demonstrated successful nickel decontamination, leading to enhanced plant growth, reduced oxidative stress, increased chlorophyll concentrations in leaves, higher micronutrient concentrations in grains, and improved relative water content. These findings are promising, as lentils are widely consumed in human and animal diets, and Ni contamination can pose risks to human and ecosystem health.

Treatment of contaminated water

Water pollution caused by the discharge of various contaminants, including pesticides (Sabo et al., 2021), heavy metals (Rahman et al., 2020), pharmaceutical products (Wöhler et al., 2021), dyes (Sheng et al., 2018), and plastics (Goddijn-Murphy and Williamson, 2019), renders it unsuitable for consumption and jeopardizes marine life, leading to significant ecosystem damage and adverse effects on human health (Sarubala, 2020; Zolkefli et al., 2020). In response to this pollution and its ramifications, it becomes imperative to optimize processes aimed at removing or reducing the concentrations of these contaminants in water. Such optimization can involve proposing new filters, enhancing existing processes, and exploring alternative methods (Zeng et al., 2021).

Various processes are available for removing contaminants from wastewater, including charcoal filtration, chemical precipitation, coagulation, reverse osmosis, and adsorption (Abreu et al., 2018). Among these, adsorption stands out as one of the most advantageous processes due to its low cost compared to alternatives and its remarkable efficacy in contaminant removal (Alam et al., 2020). It is a physicochemical method characterized by metabolic independence and a high capacity to recover various organic and inorganic substances. The adsorption process involves several mechanisms, including ion exchange, precipitation, and surface complexation (Abreu et al., 2018).

Chitosan emerges as an ideal polymer for adsorption techniques due to its abundant amino and hydroxyl groups in the polymeric chain. These functional groups serve as active sites for heavy metal retention. The density of these sites directly influences the adsorption capacity for ions and the duration of the process (Zia et al., 2020). Moreover, chitosan exhibits hydrophobic characteristics and a flexible structure, further enhancing its ability to remove contaminants (Alam et al., 2020).

The adsorption process with chitosan involves various mechanisms, including van der Waals forces, entrapment of contaminants, and ion exchange (Alam et al., 2020). Consequently, chitosan emerges as a promising candidate for heavy metal removal, given its significant binding capacity to ions such as Zn(II), Cu(II), Cd(II), Ni(II), Hg(II), and Cr(VI), as well as anions and cations present in dyes (Abreu et al., 2018). However, the effectiveness of the adsorption process depends on factors such as pH, ion type, adsorbent dosage, reaction time, temperature, and agitation speed. For instance, the optimal pH range for the process typically falls between 5.0 and 8.0. At lower pH levels, protonation of the amino group occurs, resulting in electrostatic repulsion of ions due to high concentrations of H^+. Challenges such as polymer swelling, low mechanical strength, and limited surface area can be addressed by chemically modifying the amino groups and incorporating various composites (Zia et al., 2020; Tatsumi et al., 2021).

Numerous applications of chitosan in water treatment have been explored, including the preparation of adsorbents for arsenic removal (Zeng et al., 2021), Pb(II) and other metal removal using chitosan magnetic composites (Peralta et al., 2019), virus removal with chitosan and zirconium coagulants (Christensen et al., 2017), and degradation of water contaminants using Fe-chitosan complexes (Farinelli et al., 2021). In the quest for new filter models, Janesch et al. (2020) investigated renewable chitosan filters as a cost-effective alternative for water treatment. These filters, composed of chitosan-glucan nanopapers derived from the common white-rot mushroom *Agaricus bisporus*, exhibited a copper ion adsorption capacity of up to 120 mg/g, which could be further increased based on the degree of polymer deacetylation. The addition of cellulose to the chitosan-glucan nanopapers enhanced the adsorption capacity to 162 mg/g.

Moreover, Kang et al. (2021) addressed the issue of microplastics, proposing a pretreatment method using chitosan to reduce the release of polyester microfibers from synthetic clothes during washing. The pretreatment significantly reduced polyester release, offering promising solutions for mitigating microplastic pollution in sewage.

To enhance existing filters, Coleman et al. (2021) proposed incorporating chitosan into clay filters to address the challenge of diarrheal viruses, which cause approximately 1.3 million deaths annually. However, conventional ceramic filters proved inefficient for virus filtration due to pore sizes larger than virus dimensions. To address this issue, chitosan lactate and chitosan acetate were evaluated as pretreatments, serving as cationic coagulants added to ceramic filters. The chitosan-enhanced filters exhibited a significant increase in bacteria and virus reduction compared to conventional ceramic filters, achieving >5 $\log_{10}$ reduction for *E. coli*, *Clostridium perfringens*, and various coliphages (MS2, Qβ, ΦX174, and F+). This microorganism removal efficiency was sustained over ten consecutive weeks of daily filter use. Hence, the combination of chitosan flocculation and coagulation with ceramic filtration was regarded as a straightforward and practical system for efficiently reducing the microbial load in water.

Palacio et al. (2020) investigated the use of alkylated chitosan combined with ultrafiltration membranes for the removal of antibiotics from aquatic systems. The presence of these pharmaceuticals in water has become a global concern due to their potential to promote the emergence of highly resistant bacterial strains. The antibiotics evaluated in the study were amoxicillin (AMX), tetracycline (TET), and ciprofloxacin (CIP). The highest drug retention within the polymer structure was observed at pH 11. The retention capacities for the initial antibiotic load were 185.6, 420.2, and 632.8 mg/g for CIP, AMX, and TET, respectively. However, following a second antibiotic load, the retention efficiency decreased, suggesting a strong interaction between the antibiotics and the polymer structure through hydrogen bonding. Furthermore, the polymer combined with the ultrafiltration membrane achieved removal efficiencies of 73.54%, 87.08%, and 93.83% for CIP, AMX, and TET, respectively, during the first antibiotic load. Therefore, alkylated chitosan, when combined with ultrafiltration membranes, represents a promising strategy for water treatment.

After the adsorption process, chitosan-based materials can be regenerated and reused through desorption treatments, contributing to the economic feasibility and environmental sustainability of the process. Recovery can be performed in both water treatment and soil remediation applications using acidic, alkaline, saline, or chelating eluents, such as HCl, NaOH, NaCl, and EDTA, which promote the desorption of contaminants from the active adsorption sites. Among these methods, acidic eluents are frequently reported as the most effective for recovering heavy metals adsorbed onto chitosan matrices. Following desorption, the adsorbent is generally washed with deionized water until neutral pH is achieved and subsequently dried for reuse in additional adsorption cycles. Several studies have demonstrated that chitosan composites can maintain significant adsorption efficiency after multiple regeneration cycles, reinforcing their applicability in sustainable soil and water remediation technologies (Vakili et al., 2019).

Use of recent natural chitosan composites for environmental applications

Even though chitosan has a range of applications, its utility may be restricted due to its low solubility under biological conditions, potentially hindering its usage. These limitations can be mitigated through grafting new materials, forming composites, or chemically modifying its structure. In all these cases, improvements in chemical properties and increased porosity of the biopolymer are achieved (El Knidri et al., 2018; Braz et al., 2020). Such enhancements lead to increased adsorption capacity of chitosan without compromising its characteristics of biocompatibility, mucoadhesiveness, and biodegradability (Pal et al., 2021). Table 3 showcases several chitosan composites that demonstrate superior results in the adsorption process of environmental contaminants.

For this reason, in recent decades, studies and the exploration of natural or renewable resources in composite materials (natural fibers and/or bio-based polymer matrices) have significantly increased (Das et al., 2021). According to the Web of Science Database (2024), between 2017 and 2021, 378,925 scientific articles on composites were indexed, predominantly in research areas such as materials science, engineering, chemistry, and polymer science.

Table 3 – Efficiency of pure chitosan and chitosan-composites in the adsorption of environmental pollutants

Pollutants removed	Experimental conditions	Biopolymer	Adsorption capacity (mg/g)	Composite	Adsorption capacity (mg/g)	References
Cr(VI)[2]	pH: 3; T: 25 °C	Pure Chitosan	55.51	Chitosan-silica and hydroxyapatite	212.76	Billah et al. (2021)
Phosphate[3]	pH: 3; T: 25 °C	Pure Chitosan	344.80	Chitosan and polyvinyl alcohol	384.60	Nguyen and Bui (2021)
Nitrate[3]	pH: 3; T: 25 °C	Pure Chitosan	122.00	Chitosan and polyvinyl alcohol	135.10	
Ca(II)[3]	pH: 4; T: Room temperature	Pure Chitosan	85.61	Glutaraldehyde-chitosan	180.23	Wei et al. (2021)
Cu(II)[2]	pH: 6; T: NI	Pure Chitosan	300.00	Chitosan and gum arabic nanoparticles	549.00	Abreu et al. (2018)
Reactive Blue 221[1]	pH: 5; T: 30 °C	α-Chitosan	49.01	β-chitosan cross-linked with triethylenetetramine	625.00	Chiu et al. (2018)
		β-Chitosan	54.34	β-chitosan cross-linked with triethylenetetramine	625.00	
Acid orange II (T-II)[1]	pH: 6.5; T: 25 °C	Pure Chitosan	256.41	Zirconium(IV)-chitosan	666.67	Demirçivi (2018)

Note: T: Temperature; Ca: Calcium; Cu: Copper; Cr: Chromium; [1]Dye; [2]Heavy metals; [3]Chemical compounds; NI: Not informed.

Composites are materials comprising at least two chemical species with differing physical and chemical properties. The constituents of a composite material can be categorized into matrix and reinforcement (Swolfs et al., 2019). The matrix may consist of synthetic polymers (polyester, polyamides, polypropylene, and nylon) (Zhang et al., 2021), biopolymers (vegetable cellulose, bacterial cellulose, starch, peptides, chitosan, and chitin) (Eskitoros-Togay et al., 2020; Amorim et al., 2021; Choi et al., 2021), ceramics (pearl shells, clams, ammonite shell, sponge spicules, and bones) (Amorim et al., 2021), or metals (aluminum, magnesium, titanium, and nickel) (Hu et al., 2021; Li et al., 2021b; Shao et al., 2021; Yin et al., 2021). Reinforcing materials may include particles (neodymium oxide, graphene oxide, and aluminum carbide) (Li et al., 2021b; Zhang et al., 2021), fibers (resins, silicon carbide, epoxy, glass, carbon, and polyethylene) (Das et al., 2021; Xu et al., 2021), and natural materials (aragonite, graphene, activated carbon, diatomaceous earth, zeolite, and bentonite) (Amorim et al., 2021; Peter et al., 2021; Salih and Ghosh, 2018a; Shamsudin and Shahadat, 2019).

Composites offer high availability, tensile strength, cost-effectiveness, reusability, long-term stability, low density, corrosion resistance, processability, biodegradability, and non-toxicity (Swolfs et al., 2019; Das et al., 2021). These attributes are crucial for the adsorption processes employed in environmental chemistry, energy, catalysis, or material processing (Julbe et al., 2019) because pollutant removal via adsorption is a simple, cost-effective, and flexible process. When biosorbents are utilized, they represent a sustainable technology (Salih and Ghosh, 2018b).

Composite biopolymer biosorbents serve as physical barriers primarily for water treatment applications. Their mechanism facilitates the selective transport of chemical species (gases, liquids, and/or ions), encompassing drugs, dyes, heavy metals, and inorganic salts (Yu et al., 2021). To this end, diatomaceous earth, zeolite, and bentonite have been extensively employed as reinforcement materials in chitosan polymer matrices (refer to Table 4), primarily owing to the significance of this amalgamation in enhancing adsorption capacity and facilitating reuse cycles.

Chitosan/diatomaceous earth composite

Diatomaceous earth, or diatomite, is a biogenic sedimentary rock whose surface silanol groups ($SiO_2 + nH_2O$) serve as active binding sites (Mujtaba et al., 2021). Its unique physicochemical properties, including high porosity (65%), biocompatibility, thermal stability, and a large surface area (30 m^2/g), support both conventional industrial applications, such as catalyst supports and filtration media, and emerging technologies, including 3D-printed materials and biomedical scaffolds (López-Cebral et al., 2018; Aggarwal et al., 2019; Salih et al., 2020; Zhen et al., 2020).

When incorporated into different matrices, diatomite can enhance extraction and sensing processes. For example, λ-MnO_2/diatomite composites achieve lithium extraction efficiencies of up to 95%, with a maximum adsorption capacity of 27.4 mg/g and promising reusability characteristics (Marthi and Smith, 2019; Marthi and Smith, 2021). Similarly, honeycomb-structured SnO_2/diatomite composites facilitate charge transfer and improve the detection of moisture and gases such as NO_2 and NH_3 (Zhen et al., 2020). In addition, iron oxide-modified diatomite has demonstrated the ability to remove emerging contaminants from wastewater, reaching an 88% removal efficiency for carbamazepine within 180 min (Jemutai-Kimosop et al., 2020).

The most relevant environmental application of diatomite, however, is its incorporation into chitosan matrices for wastewater treat-

Table 4 – Removal of pollutants by biopolymer composites containing chitosan and either zeolite, bentonite, or diatomaceous earth in their composition

Composites	Synthesis method	Eluent	Pollutants removed	Adsorption capacity (mg/g)	Reusability	References
Chitosan/zeolite	Drop-wise	CH_3COOH	Methyl orange[1]	287.00	NI	Hussain et al. (2021)
Chitosan/bentonite	Pillared process	0.5 mol/L NaOH	Cr(VI)[3]	133.85	6 cycles	Jia et al. (2021)
Chitosan/calcium alginate/ bentonite	Semi-dissolution-acidification-sol-gel transition	HNO_3 0.1 M	Zn[3] Pb(II)[3] Cu(II)[3] Cd(II)[3]	72.9 434.89 115.30 102.38	NI 5 cycles 5 cycles 5 cycles	Lin et al. (2021)
Chitosan/zeolite-A	Colloid solutions	0.1M CH_3COOH	Acephate[2] Omethoate[2] Methyl parathion[2]	650.70 506.50 560.80	5 cycles	Mostafa et al. (2021)
Chitosan/zeolite	Drop-wise	CH_3COOH 2%	Vanadium[3]	250.00	3 cycles	Salehi et al. (2020)
Chitosan/zeolite/zirconium	Drop-wise	CH_3COOH 2%	Vanadium[3]	265.18	3 cycles	
Chitosan/diatomaceous earth	Drop-wise	0.5M NaOH	Amido Black 10B[1] Cd(II)[3] Cu(II)[3]	132.80 108.00 97.00	10 cycles	Salih et al. (2020)
Chitosan/diatomaceous earth	Drop-wise	0.2M NaOH	As(III)[3] As(V)[3]	106.00 88.00	5 cycles	Salih et al. (2019)
Chitosan-g-poly(acrylic acid)-bentonite	Graft copolymerization	EDTA and DTPA	Cu[3] Ni(II)[3]	88.5 149.64	NI	Kumararaja et al. (2018)
Chitosan/diatomaceous earth	Drop-wise	0.2M $H_2C_2O_4$	Cr(VI)[3]	84.23	5 cycles	Salih and Ghosh (2018b)
			Zn(II)[3]	127.40	4 cycles	Salih and Ghosh (2018a)
Chitin/ZSM-5 zeolite	Nucleating gel	1 SiO_2: 0.3 Na_2O: 0.05 TPA_2O: 24 H_2O: 0.3 OH	Crystal violet[1]	1217.30	NI	Brião et al. (2017)

Note: 1: Dye; 2: Pesticides; 3: Heavy metals; 4: Drugs; **Drop-wise:** controlled and continuous drip method. **CH_3COOH:** Acetic acid; **HCl:** Hydrochloric acid; **NaOH:** Sodium hydroxide; **$H_2C_2O_4$:** Oxalic acid; **SiO_2:** Silicon dioxide; **Na_2O:** Sodium oxide; **TPA_2O**: tetrapropylammonium oxide; **H_2O:** water; **OH:** hydroxyl; **Cd:** Cadmium; **Cu:** Copper; **As:** Arsenic; **Pb:** Lead (from the Latin plumbum); **Ni:** Nickel; **Cr:** Chromium; **Zn:** Zinc; **NI:** Not informed.

ment. This synergistic composite enables the simultaneous removal of diverse pollutants, including Amido Black 10B dye, Cd(II), and Cu(II) ions (Table 4), while maintaining adsorption performance over at least ten reuse cycles (Salih et al., 2020). Furthermore, chitosan/diatomite composites have shown potential in controlled drug delivery systems by accelerating the release of hydrophilic compounds and improving the loading efficiency of hydrophobic molecules (López-Cebral et al., 2018). These characteristics further highlight the versatility, reusability, and potential of this composite for environmental and biotechnological applications.

Chitosan/zeolite composite

Zeolites are crystalline aluminosilicates organized in a polyhedral network with silicon (SiO_4) and aluminum (AlO_4) tetrahedra linked to oxygen atoms (Mittal et al., 2020). The interconnection of these molecular species in tetrahedra determines the diverse structures of zeolites, with 248 types currently known, characterized by variations in pore diameter, volume, cavity, and channel size (Hu et al., 2021). This secondary mineral possesses several key characteristics, including a high surface area, a porous structure (with pores of up to 20 Å), selectivity, ion exchange capacity, a negatively charged network, chemical and thermal stability, and condensation properties, among others (Taaca and Vasquez, 2017; Mittal et al., 2020; Salehi et al., 2020; Hu et al., 2021). These properties enable their utilization as adsorbents in conjunction with various materials such as titanium oxide (Hu et al., 2021), zirconium (Salehi et al., 2020), zinc, and silver metal ions (Mittal et al., 2020). Chitosan/zeolite composites, for instance, exhibit remarkable adsorption capabilities for metals such as Cu(II). The ability to remove heavy metals stems from zeolites' ion exchange capacity coupled with the presence of amine groups in chitosan (Taaca and Vasquez, 2017).

While natural zeolites are readily available at a low cost, they are often considered impure for certain applications due to the presence of minerals, metals, quartz, and other elements in their composition. Consequently, synthetic zeolites are primarily employed to obtain minerals with high purity, uniformity, and a large surface area. These attributes render synthetic zeolites suitable for various applications, including the development of composites for the photodegradation of organic compounds in wastewater (Hu et al., 2021) and pesticides (Mostafa et al., 2021), the more efficient removal of Cs, Ni, and Sr (Hong and Um, 2021), the elimination of antibiotics from wastewater (Szabová et al., 2022), and the removal of humic acid from aqueous solutions (Zolkefli et al., 2020).

Various methods, such as nucleation and crystallization (conventional methods), microwave-assisted hydrothermal methods, seed-assisted methods, drop-by-drop methods, molten salt and melt methods, and hydrothermal methods, are commonly employed for zeolite synthesis. Importantly, the properties of zeolites can be enhanced based on the synthesis conditions, including temperature, reaction time, matrix/reinforcement ratio, eluent, and activation processes (Hu et al., 2021).

Chitosan/bentonite composite

Bentonite is a clay formed from the erosion and weathering of volcanic ash (Qin et al., 2021). It contains numerous smectite minerals, with concentrations exceeding 60%. These minerals confer upon bentonite the property of swelling in the presence of water, resulting in low permeability values of approximately 10^{-13} m/s, indicating a high degree of compaction (Kumar et al., 2021). Additionally, bentonite comprises montmorillonite, a hydrated aluminosilicate mineral, arranged in a 2:1 layered structure, in which one alumina octahedral sheet is sandwiched between two silica tetrahedral sheets (Qin et al., 2021; Yang et al., 2021). Bentonite particles exhibit a thin circular disk morphology with a diameter of 0.1 μm. These disks possess positively charged edges, while the surface bears a negative charge, resulting in an overall negative charge for the particle (Qin et al., 2021).

Its widespread use is related to its durability, material bond strength, availability across continents, long-term storage without loss of quality, low production cost, ease of laboratory modification, thermal stability, and significant montmorillonite content (Paź et al., 2019; Purwaningrum et al., 2021). Bentonite finds extensive use as a binding material, providing support to composites and enhancing resistance, compaction, and fluidity (Paź et al., 2019). It is frequently utilized as a binding material for sand grades, improving sand's liquefaction resistance owing to bentonite's plasticity (Qin et al., 2021).

Bentonite serves as an important environmental ally, utilized in constructing barriers to encapsulate waste containing high levels of radioactivity, thereby containing the toxicity of such contaminants (Kumar et al., 2021). In addition to radiation containment, bentonite is effective in removing various pollutants (Purwaningrum et al., 2021). It can be implemented in photocatalysts to enhance the adsorption process. Bentonite exhibits superior adsorption capacity compared to other clayey materials due to cation exchange sites present on the surface, between layers, and at the edges (Yang et al., 2021).

Bentonite has been employed to remove a wide array of pollutants both individually and in mixtures. Numerous studies have focused on dye removal, such as Zhang et al. (2019), who achieved an adsorption capacity of 384.00 mg/g for Congo Red using bentonite modified with citric acid. Similarly, Stagnaro and Volzone (2019) removed orange and yellow dyes with adsorption capacities of 113 and 0.277 mmol/g, respectively, utilizing organobentonites. Other contaminants, including isopropyl alcohol, lead(II), phenol, and aniline, were efficiently removed using various bentonite composites (Ahmadi and Igwegbe, 2018; Mohajeri et al., 2018; Abdulloh et al., 2019).

Incorporating bentonite into chitosan improves the structure and adsorption efficiency, providing more active sites to trap contaminants. Bentonite/chitosan composites enhance the chelating properties of amino and azo groups, broadening the adsorption mechanism beyond carbonyl and hydroxyl groups. The stability of this composite arises from hydrogen bonds between the materials (Jia et al., 2021). Additionally, bentonite enhances the chemical and mechanical stability and ion exchange capabilities of chitosan, while chitosan improves contaminant recovery from clay particles and significantly increases material viscosity (Abu-Jdayil et al., 2021; Lin et al., 2021).

Although bentonite exhibits superior properties compared to chitosan alone, few studies have explored the combination of these two materials exclusively. Moreover, there is a scarcity of research demonstrating the possibility of composite reuse. However, existing studies underscore the efficiency of composite polymers in enhancing pollutant adsorption, particularly heavy metals, offering promising avenues for further exploration.

Discussion, limitations and future perspectives

The studies reviewed demonstrate the considerable potential of chitosan-based materials for environmental applications, particularly in pollutant adsorption, biosensing, air purification, soil remediation, and biodegradable plastics. However, despite the promising results reported, several challenges still limit the large-scale implementation of these technologies. Most studies have been conducted under controlled laboratory conditions using synthetic solutions or simplified environmental matrices, which may not accurately represent the complexity of real environmental systems.

A major limitation identified in the literature is the lack of methodological standardization. Differences in chitosan source, molecular weight, degree of deacetylation, composite composition, synthesis methods, and operational conditions hinder direct comparisons among studies and limit the identification of optimal formulations for specific applications. Furthermore, adsorption performance is strongly influenced by pH, competing ions, organic matter content, and contaminant mixtures, factors that are often insufficiently addressed in experimental investigations.

The transition from laboratory-scale experiments to real-world applications also remains a significant challenge. Although many chitosan-based composites exhibit excellent adsorption capacity and reusability, industrial implementation may require additional processing steps, regeneration procedures, and material modifications that increase operational costs and generate secondary waste streams. Consequently, comprehensive techno-economic assessments and life cycle analyses are still required to verify the actual sustainability of these technologies.

Important knowledge gaps were also identified throughout the literature. Limited information is available regarding the long-term stability of these materials, their performance under continuous operating conditions, the fate of contaminants after adsorption, and large-scale field validation. Future research should prioritize standardized methodologies, pilot-scale applications, environmentally friendly regeneration processes, and integrated assessments combining technical, economic, and environmental aspects. Addressing these challenges will be essential for translating the promising laboratory-scale performance of chitosan-based materials into effective and commercially viable environmental technologies.

Conclusion

This review emphasizes the multifunctional potential of chitosan-based composite biopolymers, explicitly highlighting their capability to adsorb emerging pollutants like heavy metals and dyes in wastewater. These composites are formed by integrating chitosan with reinforcing agents such as diatomaceous earth, zeolite, and bentonite, resulting in a hybrid structure with remarkable adsorption capacity. This efficacy is attributed to the composites' chemical selectivity and physical properties, including pore size and surface area. Moreover, these composites exhibit sustainable characteristics, low production costs, and environmental non-toxicity. Furthermore, incorporating compounds into the chitosan structure can enhance its ability to adsorb soil, air, and water contaminants, yielding recyclable, antimicrobial plastics. Lastly, this review advocates for further research on chitosan-based biomaterials to advance technological and scientific understanding and facilitate their application across various environmental sectors.

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