REVIEW

RECENT ADVANCES IN CHITOSAN-BASED MATERIALS FOR SUSTAINABLE ENVIRONMENTAL REMEDIATION: DESIGN, MECHANISMS AND APPLICATIONS – MINI REVIEW

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Abstract

Chitosan-based materials are widely investigated as sustainable adsorbents for environmental remediation due to their biodegradability, abundance, and functional versatility. This review summarises recent advances (2015–2025) in the use of chitosan and its derivatives for the removal of organic and inorganic pollutants from aqueous systems. The correlation of material structure, modification strategies, and removal efficiency are discussed, focusing on adsorption, chelation, and flocculation mechanisms. Special attention is given to hybrid and bio-integrated systems that enhance treatment efficiency through synergistic effects. Key challenges, such as limited stability, reduced performance in complex matrices, and scalability barriers, are critically evaluated. Regeneration, reusability, and life-cycle considerations are also addressed. The findings highlight the need for more application-oriented and system-level methods in future research by highlighting both the promise and present limits of chitosan-based materials. The findings indicate that chitosan-based materials demonstrate both potential and existing limitations. Future investigations should concentrate on application- and system-level approaches.

Keywords: *chitosan, chitosan-based materials, pollutant removal, remediation*

Received: 10.04.2026
Accepted: 06.08.2026

1. Introduction

The rapid growth of industrialisation and urbanisation has led to the widespread emissions of harmful chemicals into the natural environment, including hydrocarbons, heavy metals, dyes, and pharmaceuticals. These pollutants are often persistent, toxic, and bioaccumulative, posing serious threats to the environment and human health [1, 2]. While many physicochemical treatment technologies are available (chemical precipitation, membrane filtering, advanced oxidation processes, etc.), they are generally limited by high operating costs, inadequate pollutant removal, and the formation of secondary waste streams [3].

To address these barriers, a wide range of remediation technologies has been developed, including biological approaches and the use of sustainable bio-based materials. Among biological approaches, bioremediation relies on living organisms, primarily microorganisms, to degrade, transform, or detoxify environmental contaminants. In parallel, natural polymers have attracted increasing attention as environmentally friendly remediation materials. Among them, chitosan has received considerable interest owing to its abundance, biodegradability, non-toxicity, and diverse physicochemical properties [4]. Chitosan, generated from chitin, is mostly sourced from crustacean shell waste, making it a valuable commodity in the context of a circular economy and waste valorisation [5].

Several comprehensive review articles have summarised the application of chitosan and its derivatives in environmental remediation from different perspectives. For example, Pal *et al.* [6] reviewed the broad environmental applications of chitosan-based materials, whereas Keshvardoostchokami *et al.* [7] focused on the removal of nitrogen-containing pollutants from water. More recently, Issahaku *et al.* [8], Kaczorowska and Bożejewicz [9], and Dambuza *et al.* [10] provided updated overviews of chitosan-based materials, their modification strategies, and environmental applications. However, the rapid development of advanced functionalised materials, hybrid remediation systems, regeneration strategies, and application-oriented approaches highlights the need for an updated and integrated overview of recent advances in this field.

The reactive amine ($–NH_2$) and hydroxyl (–OH) functional groups in the chitosan polymer backbone facilitate the multiple interaction mechanisms with pollutants, such as adsorption, chelation, ion exchange, and flocculation, thereby enhancing chitosan's efficacy in environmental remediation [4, 11]. Consequently, chitosan has been extensively investigated for the adsorption of heavy metals such as Pb(II), Cd(II), and Cr(VI), as well as organic contaminants such as dyes and pesticides [9, 12, 13]. Moreover, the potential uses of chitosan are steadily increasing due to chemical modifications and advances in chitosan-based materials, such as hydrogels, nanofibers, beads, and nanocomposites [8, 10]. Functionalisation techniques, including cross-linking and the implementation of inorganic nanomaterials (e.g., metal oxides, graphene derivatives), improve adsorption capacity, selectivity, and mechanical stability [8, 11]. More recently, chitosan has also been incorporated into hybrid bioremediation systems by combining it with biological agents, such as microorganisms or algae, thereby integrating adsorption with microbial biodegradation to enhance pollutant removal efficiency and process stability [8, 14, 15].

The practical implementation of chitosan in large-scale environmental remediation still faces challenges, including limited mechanical strength, poor solubility in corrosive environments, and limited regeneration, despite its numerous advantages. Consequently, ongoing research is concentrated on the optimisation of chitosan-based materials and the enhancement of their efficacy under realistic environmental conditions [10, 16].

This review aims to provide a comprehensive and current overview of the use of chitosan and its derivatives in environmental remediation, focusing primarily on studies published between 2015 and 2025, including material design mechanisms, contaminant removal mechanisms, and the challenges currently facing this research field.

2. Chitosan: A Functional Biopolymer for Environmental Applications

Chitosan is a linear polyaminosaccharide composed of β-(1→4)-linked D-glucosamine and *N*-acetyl-D-glucosamine units, derived from the partial deacetylation of chitin. Its structural importance relative to cellulose, associated with the presence of amine groups, distinguishes it from other natural polymers and explains its unique reactivity and applicability [4].

The main industrial source of chitosan is chitin derived from shellfish waste, mostly the exoskeletons of shrimp, crabs, and lobsters. The use of waste in manufacturing makes chitosan production a significant instance of biomass valorisation in the circular economy [5].

The degree of deacetylation (DD) and molecular weight (MW) are critical factors that affect the physicochemical characteristics of chitosan, including solubility, charge density, and adsorption capacity. A larger degree of deacetylation (DD) often correlates with an enhanced availability of amine groups, thereby augmenting metal binding and adsorption efficiency [4, 5].

The potential of chitosan for environmental remediation (Table 1) is based on several important characteristics. Because of the protonation of its amine groups, it is soluble in diluted acidic solutions and may take on a variety of morphologies, including hydrogels, beads, films, and membranes. Strong electrostatic interactions with negatively charged pollutants, such as anionic dyes and certain organic compounds, are enabled by chitosan's cationic nature [17]. Ion exchange, coordination bonding, and hydrogen bond formation are all made easier by the presence of $–NH_2$ and –OH functional groups. Because of these characteristics, chitosan may effectively adsorb a variety of pollutants, especially heavy metals such as Cu(II), Pb(II), and Cr(VI) [12, 13]. Furthermore, chitosan is much better than synthetic polymers from an environmental perspective due to its excellent biodegradability and biocompatibility [4, 5].

Despite its advantages, native chitosan has several limitations that hinder its direct application in large-scale remediation processes. Its weak mechanical stability, especially in acidic conditions, affects its reusability and durability in aquatic systems [11, 14]. Moreover, the comparatively low specific surface area and relatively small porosity of raw chitosan may limit its adsorption capacity. In addition, its selectivity for contaminants is often insufficient to treat complex wastewater matrices containing numerous contaminants [10, 14].

To address these limitations, comprehensive research has concentrated on chemical modification and the development of composite materials. The processes of cross-linking, grafting, and the integration of inorganic nanoparticles have demonstrably enhanced structural stability, adsorption efficiency, and selectivity, hence broadening the use of chitosan in advanced remediation systems [8, 11].

Table 1. The overview of chitosan-based materials used in environmental remediation.

Type of chitosan	Form	Contaminant	Adsorption mechanism	Key advantages	Limitations	[Ref]
unmodified chitosan	powder, flakes	heavy metals (Pb(II), Cu(II), Cd(II)), dyes	adsorption, chelation	low cost, biodegradability	low stability, dissolution in acid media	[9, 14, 17, 18]
crosslinked chitosan	glutaraldehyde- and epichlorohydrin-crosslinked chitosan beads	heavy metals, dyes	chelation, ion exchange	improved mechanical strength, reusability	reduced active sites	[19, 20]
grafted chitosan	chitosan-*g*-poly(acrylic acid) hydrogel; amine-functionalised chitosan composite beads	metals, pharmaceuticals	electrostatic attraction, complexation	higher selectivity, tunable properties	more complex synthesis	[11, 21–23]
chitosan hydrogel	3D networks, cryogels	dyes, antibiotics	adsorption, diffusion-controlled uptake	high swelling capacity, large surface area	poor mechanical strength (uncrosslinked)	[24]
magnetic chitosan composite	Fe_3O_4-chitosan nanocomposite particles	heavy metals, dyes	adsorption + magnetic separation	recovery, reusability	possible nanoparticle leaching	[25]

Table 1. (continued) The overview of chitosan-based materials used in environmental remediation.

Type of chitosan	Form	Contaminant	Adsorption mechanism	Key advantages	Limitations	[Ref]
chitosan-carbon composites	chitosan/graphene oxide composite nanoparticles	dyes, pharmaceuticals	π–π interactions, adsorption	high surface area, enhanced capacity	cost, aggregation issues	[8]
chitosan-clay composites	diethanol tartaramide-crosslinked chitosan/montmorillonite composite particles	dyes, metals	adsorption, ion exchange	improved stability and porosity	moderate selectivity	[26]
modified chitosan	nanofibers	dyes, organic pollutants	adsorption, filtration	high surface-to-volume ratio	scaling challenges	[8, 27, 28]
chitosan-based biohybrids	glutaraldehyde-crosslinked-blue-green algae gels, chitosan-coated microalgae-fungal pellets	nutrients, pharmaceuticals	adsorption + biodegradation	synergistic removal	biological instability	[14, 15]
crosslinked chitosan	ZnO-crosslinked chitosan beads	Cr(VI)	adsorption	reusability	high cost	[29]
unmodified chitosan (DD 95%)	physical form not specified	reactive dyes (RB 5, RY 84; single and mixtures)	electrostatic interactions, hydrogen bonding, heterogeneous adsorption	very high adsorption capacity, high effectiveness in multicomponent systems	strong pH dependence, reduced efficiency in mixtures	[30]

3. Mechanisms of Pollutant Removal by Chitosan-Based Materials

The efficiency of chitosan-based materials in remediation is attributed to the coexistence of numerous physicochemical processes that sometimes occur simultaneously. These processes depend on the chemical structure of chitosan, particularly the amino ($–NH_2$) and hydroxyl (–OH) functional groups, and on environmental conditions (pH, ionic strength, and pollutant speciation). The contribution of each process varies with the type of contaminant and the polymer's structural properties, such as its degree of deacetylation and morphology [9, 31].

Adsorption is the primary mechanism through which chitosan and its derivatives remove pollutants from the environment, involving both physical (physisorption) and chemical (chemisorption) processes. A high density of amine and hydroxyl groups facilitates various interactions, such as electrostatic attraction, hydrogen bonding, van der Waals forces, and π–π interactions, especially in the case of aromatic contaminants [4, 31]. Under acidic conditions, amine groups become protonated ($–NH_3^+$), enabling strong interactions with negatively charged species such as anionic dyes, pharmaceuticals, and certain inorganic complexes. In contrast, at higher pH values, deprotonation promotes interactions with cationic species via coordination and ion-exchange mechanisms. In addition, recent studies have shown that the adsorption behaviour is significantly influenced by structural features such as porosity, morphology, and nanoconfinement effects. Native chitosan typically exhibits a relatively low specific surface area, which limits its adsorption capacity. Advanced chitosan forms (e.g., aerogels, nanofibers, and composites) exhibit increased adsorption correlated with greater accessibility and diffusion routes [9, 11]. These results demonstrate that the efficacy of adsorption is not just a question of chemical functionality but also of material design [12].

Chelation is crucial to the removal of heavy metals. The free electron pairs on nitrogen and oxygen atoms may form stable coordination complexes with metal ions such as Cu(II), Pb(II), Cd(II), and Cr species [4, 17]. This process involves the formation of coordination bonds between metal ions and functional groups on the chitosan backbone, often resulting in bidentate or multidentate complexes. These interactions lead to strong and selective binding of metal ions, making chitosan particularly useful for heavy metal removal [13, 32]. The efficiency of chelation is closely linked to the degree of deacetylation, which determines the availability of free amino groups [4]. Moreover, the interaction pathways can vary across metal ions. For example, Pb(II) and Cu(II) are mainly removed via coordination with amino groups, whereas Cr(VI) removal may involve a combination of adsorption and reduction processes [13]. In modified systems, e.g., grafted or composite chitosan materials, chelation is commonly paired with ion exchange and surface complexation, resulting in improved removal efficiency and selectivity [11, 13].

Chitosan is also an effective bioflocculant and coagulant, especially for the treatment of turbid wastewater and colloidal suspensions. The process is largely dependent on charge neutralisation and polymer bridging. Protonated amino groups ($–NH_3^+$) neutralise negatively charged colloids, and polymer chains enhance aggregation via inter-particle bridging to create flocs that may be readily removed by sedimentation or filtering [2, 4]. Chitosan-based flocculation has recently been shown to simultaneously remove turbidity, organic matter, and metal ions in complex wastewater systems [10]. Recent studies demonstrate that chitosan-based flocculation allows the simultaneous removal of turbidity, organic matter, and metal ions in complicated wastewater systems. Compared with synthetic coagulants, chitosan also offers biodegradability, low toxicity, and reduced secondary pollution, making it a promising sustainable alternative [10].

In advanced chitosan-based materials, pollution removal is determined by the synergistic interactions of multiple processes rather than by a single dominant process. Modern systems, such as nanocomposites and hybrid materials, include adsorption, chelation, ion exchange, and catalytic or biological processes into a single platform [11, 33, 34]. For example, chitosan-carbon composites improve adsorption by increasing surface area and π–π interactions, whereas magnetic systems combine adsorption and chelation with efficient separation [10]. This approach is advanced further in biohybrid systems, where adsorption is coupled with biodegradation to sequentially or simultaneously remove pollutants [14]. These synergistic effects substantially increase overall performance in terms of adsorption capacity, kinetics, and selectivity, and improve reusability. Therefore, current research trends focus on the development of multifunctional chitosan-based systems to address complex, multi-component environmental pollution problems.

4. Applications of Chitosan in Remediation

The effective use of chitosan-based materials for environmental remediation has markedly increased in recent years, driven by advances in materials engineering and growing environmental challenges. The initial research focused on dye removal; however, current work encompasses a broad range of contaminants, including heavy metals, pharmaceuticals, pesticides, and other emerging pollutants. Recent studies show that the efficiency of chitosan-based systems is determined not only by the material's intrinsic properties but also by environmental conditions such as pH, ionic strength, and the presence of competing species [10, 25, 35].

4.1. Heavy Metals Removal

The removal of heavy metals is the most thoroughly researched application of chitosan-based polymers, owing to their strong affinity for metal ions. This affinity arises from the presence of amino and hydroxyl groups, which facilitate coordination, chelation, and ion exchange [4, 17]. Recent studies indicate that modified chitosan materials-especially nanocomposites and functionalised derivatives-show markedly superior adsorption capabilities relative to native chitosan [25, 35]. Adsorption capacities often exceed 150–300 mg/g for metals such as Pb(II), Cu(II), and Cd(II), depending on the material structure and experimental conditions [12, 25]. Magnetic chitosan composites and thiol-functionalised derivatives exhibit exceptional efficiency and selectivity, attributed to the increased number of active binding sites and enhanced recovery properties [11, 12, 35]. Moreover, recent research has shown enhanced performance in multicomponent systems upon incorporation of chitosan into hybrid or nanocomposite matrices [36].

Nevertheless, numerous significant limitations remain. Competing ions (e.g., Ca^{2+}, Mg^{2+}) can significantly reduce adsorption effectiveness, whereas pH-dependent metal speciation substantially impacts removal efficacy [12, 25]. These limitations restrict the simple translation of laboratory results to real wastewater systems.

4.2. Removal of Organic Pollutants (Dyes, Pesticides, Pharmaceuticals)

Chitosan-based materials have been extensively employed to eliminate organic pollutants, including synthetic dyes and, more recently, pharmaceuticals and pesticides. In the case of aromatic molecules, the adsorption of organic compounds is influenced by π–π interactions, hydrogen bonding, and electrostatic interactions [3, 27]. The adsorption

performance of nanocomposite systems, particularly those incorporating graphene oxide or other carbon-based materials, has been significantly improved in recent studies. This is attributed to the increased surface area and additional interaction mechanisms [25, 36]. Adsorption capacities exceeding 300 mg/g have been reported for specific dye systems under optimised conditions [30, 31].

For pharmaceuticals and pesticides, the adsorption behaviour is considerably more complex and significantly influenced by the molecular structure and solution chemistry. Recent research indicates that functionalised chitosan materials can effectively remove antibiotics and endocrine-disrupting compounds. However, the adsorption efficiency is generally lower than that of dyes due to weaker interactions and competitive effects [33, 35, 37].

In complex matrices containing numerous organic pollutants, the reduced efficiency of chitosan-based materials is a significant limitation that has been recently highlighted in the literature. This is due to significant competitive adsorption and fouling effects [10, 25].

Chitosan-based materials have shown very high effectiveness in the removal of anionic dyes, mainly due to strong electrostatic interactions between protonated amino groups and negatively charged dye molecules. Many studies report excellent adsorption performance in single-solute systems, but recent work has focused on more realistic multicomponent systems. Filipkowska and Jóźwiak [30] have studied the sorption of reactive dyes onto chitosan in single- and binary-dye systems. The authors obtained very high adsorption capacities up to 742 mg/g for Reactive Black 5 (RB 5) and 760 mg/g for Reactive Yellow 84 (RY 84) in single-component solutions. Notably, the adsorption capabilities of 528 mg/g and 437 mg/g were observed in competing systems. The adsorption process was best fitted by a double-Langmuir model, suggesting heterogeneous binding sites and complex adsorption behaviour [30]. These results show that chitosan-based materials could be useful for real-world pollution, where multiple toxins are present simultaneously. However, the decrease in binding capacity in binary systems underscores the importance of competitive effects, which are rarely considered in simple lab studies.

4.3. Emerging Contaminants

Recent research has primarily focused on the removal of emerging contaminants, such as pharmaceuticals, personal care products, and endocrine-disrupting compounds. These pollutants are characterised by low concentrations, high persistence, and significant biological activity. Recent research has shown that chitosan-based materials, particularly hybrid and nanocomposite systems, can effectively eliminate specific emerging contaminants through a combination of catalytic or biological processes and adsorption [10, 33]. For example, chitosan-based photocatalytic composites have been shown to be capable of combining both adsorption and degradation, thereby improving overall removal efficiency [36].

Nonetheless, in comparison to heavy metals and dyes, the elimination of emerging pollutants is less effective and more variable. Adsorption capacities are typically lower, ranging from 50–150 mg/g, with underlying mechanisms more intricate, involving multiple interactions and transformation pathways [33]. Therefore, the present research has become more focused on the development of multifunctional materials that integrate adsorption with degradation or biotransformation processes, such as photocatalytic or biohybrid systems.

5. Integration of Chitosan with Biological Systems

The integration of biological systems with chitosan-based materials enables the coordination of biodegradation and adsorption mechanisms, leading to improved process stability and increased removal efficiency (Table 2). Recent studies have demonstrated that hybrid systems integrating chitosan with biological components, such as bacteria, fungi or microalgae, combine adsorption with biodegradation, enabling more efficient removal of complex or low-concentration pollutants [14, 15]. In these systems, chitosan not only acts as an adsorbent but also serves as an immobilisation matrix that enhances microbial stability, biomass retention, and resistance to environmental stress, thereby improving the overall treatment performance [15, 38].

Chitosan-based materials integrated into biological systems demonstrate significant potential for environmental remediation, particularly through microbial immobilisation, microalgal systems, fungal immobilisation, and membrane bioreactor applications. Immobilisation of microbes within a chitosan matrix considerably improves biodegradation efficacy by increasing cell density, improving resistance to toxic compounds, and facilitating biomass retention [15, 38]. Chitosan-immobilised microbial and microalgal systems have demonstrated enhanced pollutant removal compared with freely suspended cells, although the performance strongly depends on the microbial community, pollutant type, and operational conditions. For example, chitosan-immobilised *Scenedesmus* achieved 70% nitrate removal and 94% phosphate removal within 12 h, while free-living cells removed only 20% nitrate and 30% phosphate within 36 h [39]. Similarly, indigenous siderophore-producing bacterial communities immobilised in chitosan beads achieved approximately 90% decolourisation of Acid Black 1 and Reactive Black 5 within 72 h through the combined action of biosorption and biodegradation [40]. Moreover, chitosan immobilisation facilitates biomass recovery and improves operational stability by preventing biomass washout and maintaining high cell viability. However, diffusion limitations may occur in highly cross-linked matrices, particularly when treating larger molecules or operating at high biomass densities [41]. Immobilisation of *Aspergillus sydowii* in γ-Fe_2O_3 magnetic chitosan beads further demonstrated the versatility of chitosan-based carriers, enabling the simultaneous removal of trichlorfon and Cd(II) while allowing magnetic separation and reuse of the immobilised biocatalyst for four consecutive cycles [42].

Algae-chitosan systems demonstrated efficient removal of nutrients, including total nitrogen (TN) and total phosphorus (TP), as well as heavy metals, while simultaneously improving biomass harvesting through bioflocculation. In chitosan-immobilised *Scenedesmus* systems, phosphate and nitrate removal efficiencies reached 94% and 70%, respectively, demonstrating the advantages of chitosan as an immobilisation matrix for microalgae [39]. More recently, chitosan-based algal composites have also been successfully applied to the removal of organic pollutants and heavy metals, while improving biomass recovery and operational stability [14, 15]. More recently, chitosan-coated microalgae-fungal pellets achieved 98.5% chemical oxygen demand (COD), 90.2% total nitrogen (TN), 79.5% total phosphorus (TP), and 71.2% CO_2 removal in a 30-L bubble-column photobioreactor while maintaining excellent pellet stability during long-term operation [16]. These findings demonstrate that chitosan not only improves nutrient removal but also enhances biomass retention and operational stability during process scale-up. Although limitations such as light penetration and mass transfer constraints remain pertinent, these systems can maintain stable performance over multiple cycles.

Table 2. Integration of chitosan with biological systems for contaminant removal.

System type	Biological component	Chitosan material	Target pollutant(s)	Representative removal performance	Main advantage	[Ref]
immobilised bacterial community	indigenous siderophore-producing bacterial community	chitosan beads	Acid Black 1, Reactive Black 5	~90% decolorisation after 72 h	enhanced biosorption and biodegradation, improved bacterial stability and reusability	[40]
immobilised microalgae	*Scenedesmus* sp.	chitosan beads	nitrate, phosphate	70% nitrate and 94% phosphate removal within 12 h	enhanced nutrient removal, improved cell retention and sustained microalgal viability	[39]
immobilised fungi	*Aspergillus sydowii*	γ-Fe_2O_3 magnetic chitosan beads	trichlorfon (TCF), Cd(II)	135.43 mg/g (TCF) and 56.40 mg/g (Cd^{2+}) at 200 mg/L TCF and 50 mg/L Cd^{2+} using 38 mg MCBAs (120 h)	magnetic recovery, simultaneous biodegradation and biosorption, reusable for four cycles	[42]
chitosan-coated microalgae-fungal pellets	*Scenedesmus* sp. + *Aspergillus tubingensis*	0.4% chitosan coating	COD, TN, TP, CO_2	98.5% COD, 90.2% TN, 79.5% TP and 71.2% CO_2 removal (30-L BC-PBR)	improved pellet stability, biomass retention and successful scale-up	[15]
membrane bioreactor (MBR)	activated sludge	positively charged chitosan nanoparticles	membrane fouling associated with EPS/SMP during wastewater treatment	68% MBR performance index; 43.7% recovery ratio; ~97% membrane pore fouling reduction	synergistic fouling mitigation through adsorption and electrochemical processes	[43]

The efficiency and stability of treatment are enhanced in bioreactor applications using chitosan-based materials as biofilm carriers. Chitosan-based supports improve microbial adhesion, promote biofilm formation, facilitate biomass retention, and enhance the resistance of immobilised microorganisms to environmental stress [38, 41–43]. In membrane bioreactor systems, positively charged chitosan nanoparticles have also been shown to mitigate membrane fouling by modifying sludge characteristics and reducing the accumulation of extracellular polymeric substances (EPS) and soluble microbial products (SMP) on the membrane surface, thereby improving membrane recovery and reactor performance. However, the long-term durability may be limited by material biodegradation [43].

Overall, recent studies demonstrate that integrating adsorption with biological processes via chitosan-based hybrid systems offers an effective strategy for removing a wide range of contaminants while improving biomass retention, process stability, and overall treatment efficiency.

6. Regeneration and Life-Cycle Aspects of Chitosan-Based Materials in Environmental Applications

The practical use of chitosan-based materials in environmental remediation depends not only on their adsorption capacity and removal efficiency but also on their regeneration potential, reusability, and overall environmental impact. These features are crucial for process economics and long-term sustainability and have gained increased attention in recent years [2, 38, 43].

Regeneration of chitosan-based adsorbents is typically achieved by chemical desorption with acidic, alkaline, or chelating agents, depending on the dominant adsorption mechanism. Acidic solutions are often used for heavy metals, as the protonation of amino groups weakens coordination interactions, whereas alkaline or organic eluents are preferred for organic pollutants like dyes and pharmaceuticals [2, 12]. While regeneration efficiencies of approximately 70–95% have been documented for the first cycle, repeated use leads to progressive performance loss owing to structural breakdown, fouling, and incomplete desorption [35, 43].

Material design is an important factor in improving regeneration stability. Cross-linked and composite systems, such as magnetic and nanostructured chitosan, exhibit greater resistance to chemical and mechanical degradation than native materials [18, 44]. However, many reported systems remain stable for only 3–5 regeneration cycles and frequently exhibit a 10–30% loss of adsorption efficiency, mainly due to irreversible binding and the loss of active sites [12].

From a systems perspective, regeneration and reuse should be considered within a cyclic operational framework. As shown in Figure 1, the adsorption-desorption cycle is fundamentally linked to a trade-off among removal efficiency, material stability, and environmental sustainability. Regeneration increases resource efficiency but may increase the use of chemicals and energy, especially if strong eluents are required.

As a biodegradable, renewable material derived from biomass, chitosan supports the concepts of the circular economy [2, 43]. However, modification and processing steps, such as the use of crosslinkers and energy-intensive synthesis methods, significantly impact overall environmental sustainability [44]. While biodegradability is valuable at the end-of-life phase, it may simultaneously reduce durability during long-term operation, highlighting the need for a balanced compromise between material stability and environmental compatibility.

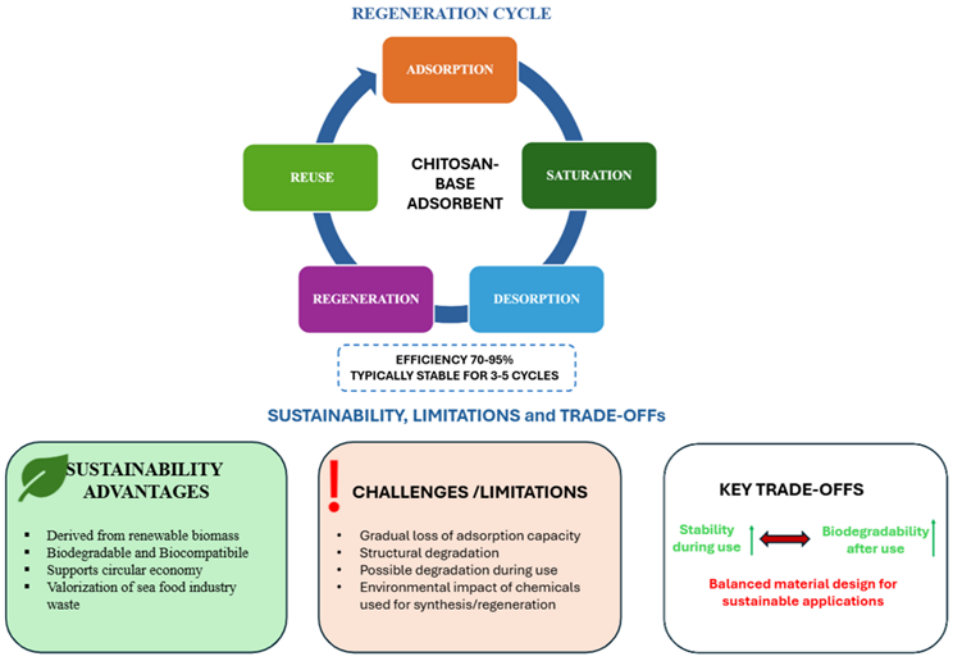

Figure 1. Regeneration cycle and sustainability framework of chitosan-based adsorbents.

Although substantial progress has been made, regeneration and life-cycle aspects remain inadequately addressed. A significant number of studies continue to concentrate on single-cycle adsorption under ideal conditions, with a limited assessment of long-term performance under realistic wastewater conditions. The absence of standardised regeneration protocols, insufficient multi-cycle testing, and limited incorporation of life-cycle assessment (LCA) into material development represent important research gaps [35]. Addressing these challenges is crucial to successfully translating laboratory-scale results into scalable, sustainable green technologies.

7. Conclusions and Future Perspectives

Chitosan-based materials are emerging as attractive bio-based adsorbents for environmental remediation owing to their biodegradability, functional flexibility, and compatibility with physicochemical and biological processes. Recent advances in crosslinking, surface functionalisation, and the development of nanocomposite materials have greatly increased their adsorption capacity and overall performance [38, 43]. However, their practical application remains limited by several technical challenges. The gap between laboratory results and real-world conditions is a critical issue, as adsorption performance is frequently reduced by complex matrices and competing ions. In addition, scalability constraints, limited stability, and declining performance across repeated cycles remain substantial challenges. Further research should focus on evaluating chitosan-based materials under realistic operating conditions, improving regeneration efficiency and long-term durability, and developing scalable and environmentally sustainable fabrication strategies. Special attention should be given to multifunctional systems that combine adsorption with catalytic or biological processes, thereby enabling

the effective treatment of complex pollutant mixtures. Bridging the gap between material design and practical application through interdisciplinary research and pilot-scale validation is crucial for the successful implementation of chitosan-based materials in environmental remediation.

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