Chitosan based materials for environmental application

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Abstract. Known for their renewable, biodegradable, and non-toxic nature, chitosan is a natural biopolymer. It is used in many fields, from the biomedical one for its biocompatibility, hemostatic, and antibacterial properties, to environmental remediation, where its biodegradability, good chelating capacity for heavy metals retaining, and cationic nature for organic pollutants chemisorption capacity are appreciated. This review summarizes the chitosan-based materials main physicochemical properties which qualifies it in environmental remediation and explores their applications in air purification, wastewater treatments, and soil remediation. Another essential aspect concerning the sustainability of chitosan-based remediation materials - regeneration and reusability was also approached in this paper. Future perspectives for chitosan-based materials in the context of drawback and them diminish measures were also highlighted. Their eco-friendly nature, combined with cost effective synthesis, makes chitosan-based remediation materials feasible natural material able to replace synthetic non-reusable polymers in environmental applications.

1 Introduction

Industrial even domestic activities generate more and more by-products and wastes that induces global environmental concerns arising from air, soil, water, and groundwater pollution [1]. Airborne pollutants, particularly volatile organic compounds (VOCs), particulate matter (PM_{10}, $PM_{2.5}$) and nanomaterials, and toxic gases are generated by industrial processes, urban transport, domestic heating systems, and more recently by nanotechnology development [2]. In case of contaminated water and groundwater with pollutants such as heavy metals, dyes, organic and inorganic compounds that are highly harmful for all humans, animals, plants and soil, their removal represent an essential goal for environmental protection [3]. Worldwide plastic materials maladministration practices generate pollution of both aquatic and ground environments and represented one of the most important targets for a sustainable health assurance [4]. Also, pharmaceuticals, especially antibiotics or analgesics, are significant intrusive pollutants

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of surface waters, by them accumulation in aquatic organisms, antibiotic-resistant bacteria promotion, representing enduring threats to ecosystems and human health [5]. In recent decades, the growing interest for sustainable and environmentally friendly materials led to biopolymers derived from renewable resources. Therefore, plants waste such as rice husks, fruit wastes, spent grains or weeds became valuable resources for low-cost adsorbents production for heavy metal ions removing from wastewater, as substitutes for more expensive conventional ones. The results indicated that such alternative showed good adsorption capacities for some heavy metals (Cd, Cu, Pb, Zn and Ni) after costly improvements, and the new solutions become “less environmentally friendly” [6]. As concerns over global challenges, chitosan-based materials offer a promising and green solution for these addressing. Chitosan (CS) is one of the most versatile and widely studied natural polymers, obtained through the partial deacetylation of chitin, a polysaccharide abundantly found in the exoskeletons of crustaceans such as shrimp, crabs, and lobsters, as well as in the cell walls of fungi and insects [7].

Chemically, CS is constituted of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units that in acidic environments own cationic character from amino-functional groups, distinguishes it from many other natural polymers, which are typically neutral or anionic. Unlike synthetic polymers derived from non-renewable sources, biodegradable nature of chitosan ensures no negative contribution to long-term pollution or microplastic accumulation. This positive charge enables chitosan to interact strongly with a variety of negatively charged species, including heavy metal ions, dyes, and organic pollutants [8]. In addition to its high adsorption capacity, porous chitosan scaffolds exhibit advantageous properties such as biodegradability and non-toxicity in the natural environmental conditions, film-forming facility that service to filtering membrane manufacturing, and antimicrobial activity that combat the microbial film formation on the filtering system or crops pests and sustain the utilization diversification fields . CS’s chemical versatility permitted a wide array of functional changes, including grafting, crosslinking, and nanoparticle incorporation, those enhanced its selectivity, stability, and performance under various environmental conditions in various applications . Properties such as biocompatibility, haemostatic, antibacterial and anti-inflammatory effects, due to the chemical composition and the cationic polymer character, determine the use of this material in the following fields: biomedical for bone implants and augmentation, skin repair and wound dressing; in the pharmaceutical industry as a substrate for sustained-release drugs or alkaline resistant shell for capsules, beverages, amino acid production; in the food field as films for coating with antimicrobial, humidity; in biotechnology field in biofuel cell or biodiesel production[9].

For the environmental pollution mitigate, should be developed sustainable, low-cost, renewable and in the same time efficient materials in order to fulfil increasingly severe regulations on water quality, air emissions, and soil contamination. Chitosan-based materials, due to their multifunctional characteristics, have been the subject of extensive research in recent years. This mini-review aims to summarize recent advances in the development and application of chitosan-based materials for environmental remediation, with a focus on their use in agricultural field such as soil amendments as well as fertility enhancement, and pollutant sensing technologies. Special attention is paid to emerging trends, hybrid materials, and the challenges associated with scalability, reusability, and

 https://doi.org/10.1051/e3sconf/202565904007

long-term performance. These attributes make it a compelling candidate for a wide range of applications particularly in water treatment, air purification, soil amendment.

2 Chitosan based materials: key characteristics and environmental relevance properties

Chitosan is a linear polysaccharide consisting of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units and derived from the deacetylation of chitin provided by crustaceans' exoskeletons (crab, shrimp, lobster, etc.) whose shells contain 20–40% protein, 20–50% calcium carbonate, and 15– 40% chitin [10]. Therefore, chitin after treatment contains a maximum of 40% amine group (—NH_2), while in chitosan, for a proper cationic reactivity, this functional group should be more than 60% [7]. The 2D structures of chitin and chitosan molecules are represented in Figure 1 [11]. The polyelectrolytic nature and chelating capacity of chitosan macromolecules, based on polar groups: protonated amino groups (NH_4^+) in an acidic solution, the hydroxyl moieties and H-bonding are responsible for the solubility behaviour of CS . In addition, the degree of deacetylation, the molecular mass of the polymer, and polymer chain ends, dictated by the synthesis conditions from chitin, are the most important factors in generating these characteristics. Free amino groups of CS chains with good deacetylate degree (>70%) are involved in chitosan-metal ions complexes formation, which affect its thermal stability and cross-linking ability, and hydroxyl groups that are involved in the degree of solubility as far as the energy of a single chitosan monomer for water binding is higher than that of chitin [12]. Distinctive applications in the medical and food industries, today CS is used in technical fields for its interesting attributes, including antimicrobial skill, antioxidant activity, adhesive potential, and notable biodegradability effect [13].

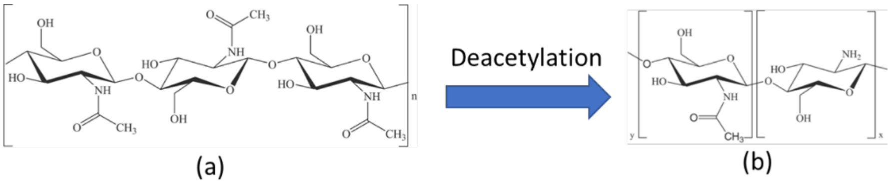

Fig. 1. The formula structure of (a) chitine, and (b) chitosan polymer [11]

Chitosan's antioxidant properties arise from amino groups, which interact with hydrogen atoms, transforming the ammonia ions into stable macromolecules that effectively neutralize harmful free radicals. Likewise, chitosan's antibacterial capacity is due to electrostatic interactions between the positively charged amino groups scattered along its molecular chain and their negatively charged counterparts, which destroy the bacterial cell membrane[14]. While chitosan has found numerous applications, its limited solubility remains a challenge. The formation of chitosan-based gels creates the premise for expanding them utilization domains as far as hydrogels are flexible, moisture-retaining materials with a three-dimensional, porous structure that resists at dissolution, with exceptional elongation properties allowing to be shaped into various forms (such as fibres, spheres, porous scaffolds, etc.), making them highly versatile[15].

From an environmental perspective, CS is notably relevant due to its sustainability and ecological safety, which support circular economy strategies and reduce environmental impact. The relevant CS feature for environmental applications was illustrated in Figure 2. Furthermore, chitosan's strong affinity for a wide range of pollutants, such as heavy metals, organic dyes, pharmaceuticals, and nutrients, has made it a valuable component in the design of adsorbents, membranes, and nanocomposites for environmental remediation . Its capacity for chemical modification and integration with other functional materials further boosts its effectiveness and versatility in specific environmental applications.

Fig. 2. Chitosan and the important roles in environmental protection

3 Chitosan in agricultural applications

Soil contamination from heavy metals, pesticides, hydrocarbons, and persistent organic pollutants is a growing global concern, threatening food safety, groundwater quality, and ecosystem health. Despite chitosan's capacity to interact with soil pollutants through adsorption, chelation, and surface complexation, like other adsorbents, it behaves in water and air purification; however, the accumulation of these pollutants into any kind of sorbents leads to a harmful increase in their concentrations in the upper layers of the soil. Chitosan can improve soil quality by soil structure and water retention enhancing, acting as a slow-release fertilizer carrier, plant growth stimulating and defences mechanisms to improve microbial activity and diversity.

2.1 Soil Amendments and Fertility Enhancement

Chitosan's properties vary with its molecular weight and acetylation degree, highlighting its usefulness in horticultural crops as a growth enhancer and antimicrobial agent that stimulates plant defences mechanisms. Chitosan and its derivatives (chitosan-coated biochar or chitosan–zeolite composites) can immobilize pollutants in contaminated soils, minimizing leaching and plant uptake[16]. In this context, its effect on soil mechanical properties has not been studied enough. Two types of chitosan with different molecular masses and deacetylation degrees, utilized as a powder additive for four soil types, were subjected to 1 - 10 wetting–drying cycles. It was observed that the influence of higher chitosan doses reduced mechanical stability and increased porosity for all soil types, except neutral soil Fluvisol, where the strength of the soil increased. After 10 cycles, acidic soils showed increased strength, while neutral and alkaline soils weakened. Additionally, coarse chitosan particles can loosen the soil structure and increase porosity, thereby reducing mechanical and water stability; however, in clay-rich soils, they may enhance mechanical strength. Conversely, electrostatic bonding between positively charged chitosan and negatively charged soil components can improve both mechanical and water stability [17]. The application of low-weight molecular chitosan solutions to rapeseed (*Brassica chinensis*) has been reported to demonstrate a favourable germination rate, seedling growth, and root length, as well as increased crop yields in beans, potatoes, and chili, and reduced disease caused by viruses, bacteria, and fungi [18]. Also, it was reported that CS (200–500 kDa) has a prompting effect on tomato (*Solanum lycopersicum L.)* and pea (*Pisum sativum L.*) plant growth and defences against both biotic and abiotic stresses [19]. Furthermore, it was observed that the fruit and seed yields of *Capsicum annuum* increased after 1% CS (970 kDa) was mixed with the ground material, which might also reduce salinity [20]. Chitosan's derivatives obtained through enzymatic degradation with *Pectinex* Ultra SPL were assessed for their ability to protect tobacco plants against *Phytophthora parasitica nicotianae*. The 24-hour hydrolysate showed the highest antipathogenic activity, while native chitosan was the least effective. In vitro tests revealed that chitosan with a low degree of acetylation (DA 1%) completely inhibited three *P. parasitica* strains at concentrations of 500–1000 mg/L, unlike the more acetylated form (DA 36.5%).

Among polymers with similar molecular weights, lower DA consistently resulted in stronger pathogen suppression, with degraded chitosan being the most potent [21]. Drought stress negatively impacted barley growth, reducing plant height, leaf number, chlorophyll content, relative water content, grain weight, yield, and key leaf anatomical traits. The application of biochar and chitosan led to significant increases in plant height, leaf number, and chlorophyll concentration as well as relative water content, growth traits, and water status while reducing electrolyte leakage and lipid peroxidation levels in stressed plants [22].

A comprehensive study concerning root-applied chitosan shows concentration-dependent effects on shoot growth—where low doses tend to enhance growth, while high doses may hinder development. Chitosan nanoparticles also offer potential for delivering biocontrol agents. Overall, root chitosan treatment holds promise for enhancing plant defence and reducing reliance on chemical fungicides, though further research is needed to assess long-term effects and optimize [23]. In lettuce, low chitosan concentrations (0.05–0.2%) significantly increased leaf number, leaf area, and shoot biomass, with fresh weight rising by 26–39%.

However, at 0.3% chitosan, all growth parameters declined, including a 26% drop in fresh weight [24]. In tomato, 0.005% chitosan in nutrient solution increased shoot dry weight by 31% after 30 days, while 0.03% reduced it by 19%. The reduction was more pronounced with the beneficial nematode *Pochonia chlamydosporia*, showing a 58% decrease at 0.03% chitosan [25].

4 Conclusions

Chitosan, a naturally derived, biodegradable, and chemically versatile biopolymer, has attracted growing attention due to its low ecological footprint and multifunctional roles in sustainable environmental applications. While its use in water treatment is well established, recent advances have begun to uncover its significant potential soil amendments, and improving soil fertility. With intrinsic properties such as a high density of active functional groups, antimicrobial behaviour, and the ability to be chemically modified, chitosan serves as a promising platform for developing eco-friendly and efficient air filtration systems. Several drawbacks widespread the intensive utilization of chitosan-based materials in air purification, including their sensitivity to extreme humidity or high temperatures, limited regeneration capability, and scalability concerns. Present chitin extraction chemical methods require lot of chemicals, and they are expensive; therefore, future actions should focus on new non-invasive synthesis methods. However, emerging research into chitosan hybrid composites, with nanostructured materials utilization, including innovative photocatalytic components offers promising routes to overcome these limitations. Chitosan-based materials future efforts should focus on optimizing their physicochemical performances under real-world operating conditions, exploring renewable feedstocks and green processing methods, integrating smart sensing capabilities, and conducting thorough life cycle assessments to quantify the true sustainability of these materials. With continued innovation and interdisciplinary collaboration, chitosan-based technologies are well-positioned to contribute to the next generation of green solutions for environmental pollution control.

This work has been carried out through the Core Program *BIO-CliMission* of the National Plan for Research, Development and Innovation 2022-2027, carried out with the support of MCID, project no. PN 23 31 03 01.

References

1. G. Deak, N. Raischi, M. Matei, M. Boboc, G. Cornateanu, M. Raischi, S. Matei, S. Yasina Yusuf, IOP Conf. Ser.: EES **616**, 012003 (2020)
2. M. Iqbal Hidayat, M. Adlim, S. Suhartono, Z. Hayati, N. Hana Hanif Abu Bakar, Arab. J. Chem. **16**, 104967 (2023)
3. D. Andreea Ioana, E. Holban, M. Boboc, M. Raischi, M. Matei, G. Deak, V. Daescu, J. Environ. Prot. Ecol. **18**, 304-312 (2017)
4. C. Maria, G. Deak, G. Tudor, E. Holban, C. Zamfir, A. Ivanov, G. Grigore, N. Rahim, Int. J. Conserv. Sci. **14**, 663-670 (2023)
5. C. Maria, G. Deak, A. Ivanov, C. Pop, G. Ghita, I. Mihaela, C. Zamfir, G. Grigore, E3S Web Conf., **437**, 02010 (2023)

   W. Ngah, L.C. Teong, M.A.K. Megat Hanafiah, Carbohydr. Polym., **83,** 1446-1456 (2011)
6. M. Chelu, A.M. Musuc, M. Popa, J.M. Calderon Moreno, Gels, **9** (2023).
7. P. Guerrero, A. Muxika, I. Zarandona, K. de la Caba, Carbohydr Polym, **206**, 820-826 (2019).

8. Y. Moussaoui, N. Mnasri, E. Elaloui, R. Ben Salem, S. Lagerge, L.C. de Menorval, EPJ Web Conf., **29** (2012)
9. S. E. Z. Syeda, M. S. Khan, A.M. Skwierawska, Desal.Water Treat., **320**, 100679 (2024).
10. H. Peidayesh, Z. Ahmadi, H. A. Khonakdar, M. Abdouss, I. Chodák, Polym. Adv. Technol., **31**, 1256-1269 (2020)
11. F. Hong, P. Qiu, Y. Wang, P. Ren, J. Liu, J. Zhao, D. Gou, Food Chem X, **21**, 101095 (2024).
12. A.Z. Hameed, S.A. Raj, J. Kandasamy, M.A. Baghdadi, M.A. Shahzad, Polymers (Basel), **14** (2022).
13. C. Brasselet, G. Pierre, P. Dubessay, M. Dols-Lafargue, J. Coulon, J. Maupeu, A. Vallet-Courbin, H. de Baynast, T. Doco, P. Michaud, C. Delattre, Appl. Sci., **9** (2019).
14. I. Corazzari, R. Nisticò, F. Turci, M.G. Faga, F. Franzoso, S. Tabasso, G. Magnacca, Polym. Degrad. Stab., **112,** 1-9 (2015).
15. A. Adamczuk, G. Jozefaciuk, Molecules, **27,** 2273 (2022).
16. D. Katiyar, A. Hemantaranjan, B. Singh, A. Bhanu, APAR, **6** (2014).
17. M. Malerba, R. Cerana, IJMS, **17**, 996 (2016).
18. K.-M. Marcelina, N. Fornal, JEE, **19**, 143-149 (2018).
19. A. Falcón, J.C. Cabrera, D. Costales, M. Ramírez-Arrebato, G. Cabrera-Barjas, V. Toledo, M. Martínez-Téllez, World J. Microbiol. Biotechnol., **24**, 103-112 (2008).
20. Y. Hafez, K. Attia, S. Alamery, A. Ghazy, A. Al-Doss, E. Ibrahim, E. Rashwan, L. El-Maghraby, A. Awad, K. Abdelaal, Agronomy, **10**, 630 (2020).
21. P. Suwanchaikasem, A. Idnurm, J. Selby-Pham, R. Walker, B.A. Boughton, J. Plant Growth Regul., **43**, 3424-3445 (2024).
22. C. Xu, B. Mou, HortTechnology, **28**, 476-480 (2018).
23. N. Escudero, F. Lopez-Moya, Z. Ghahremani, E.A. Zavala-Gonzalez, A. Alaguero-Cordovilla, C. Ros-Ibañez, A. Lacasa, F.J. Sorribas, L.V. Lopez-Llorca, Front. Plant Sci., **8** (2017).