

REVIEW

POSSIBILITIES AND LIMITATIONS OF CHITOSAN-BASED ADSORBENTS USED TO REMOVE ORGANIC AND INORGANIC CONTAMINANTS FROM AQUEOUS SOLUTIONS

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Abstract

Chitosan, as a natural biopolymer obtained from recycled sources, has a high affinity for removing various contaminants present in water systems, ranging from metal compounds, dyes, to pharmaceuticals. It has been demonstrated that modified chitosan can be successfully used to remove contaminants from various environmental matrices. This review presents the advantages and limitations of chitosan-based adsorbents that remove organic and inorganic pollutants from water and wastewater. It explains how chemical and physical modifications affect the adsorption properties of chitosan adsorbents. In addition, the possibility of the regeneration of materials used in the adsorption process is indicated.

Keywords: *chitosan-based adsorbent, modification, regeneration, removal of contaminants*

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1. Introduction

The most common pollutants in aquatic systems are metal compounds, including toxic metals, organic dyes, or emerging contaminants (such as pharmaceuticals, cosmetics, etc.). Considering the significant pollution of water and sewage resulting from human activity (industry, urbanisation, agricultural activity, etc.), we are currently looking for effective methods for pollutant separation [1, 2]. The adsorption process has been successfully used for this purpose. The adsorption process is relatively cheap, and the possibility of selecting adsorbents allows the process to be controlled in the way to achieve the highest possible separation efficiency. The main advantage of this process is the possibility of using environmentally friendly adsorbents, e.g., biochar, graphene, metal oxide modified materials, etc. [3], as well as naturally-derived sorption materials such as chitosan.

In recent years, there has been an increase in seafood consumption, which has led to an increase in shell waste. Therefore, it is necessary to find a convenient way to use them. Due to the slow and challenging process of shell decomposition, the production of chitosan (CS) by deacetylation of chitin (being a main shell component) has become an environmentally friendly process, not only because of the reduction of shell waste but also because of the specific properties of chitosan [4, 5]. Chitin is extracted from various sources, such as the shells of crabs and shrimps, the exoskeletons of insects, and the cell walls of certain species of fungi and algae. Various chitin polymeric forms are present in shrimp and crab shells, squid tentacles, and cephalopods' stomach lining: α -, β -, and γ -chitin, respectively (Figure 1). In chitosan, the $-\text{OH}$ group on the second carbon atom of cellulose is replaced by an acetyl $-\text{NH}_2$ group. Therefore, chitosan is a copolymer consisting of two repeating units, i.e., *N*-acetyl-2-amino-2-D-glucopyranose and 2-amino-2-deoxy-D-glucopyranose [6].

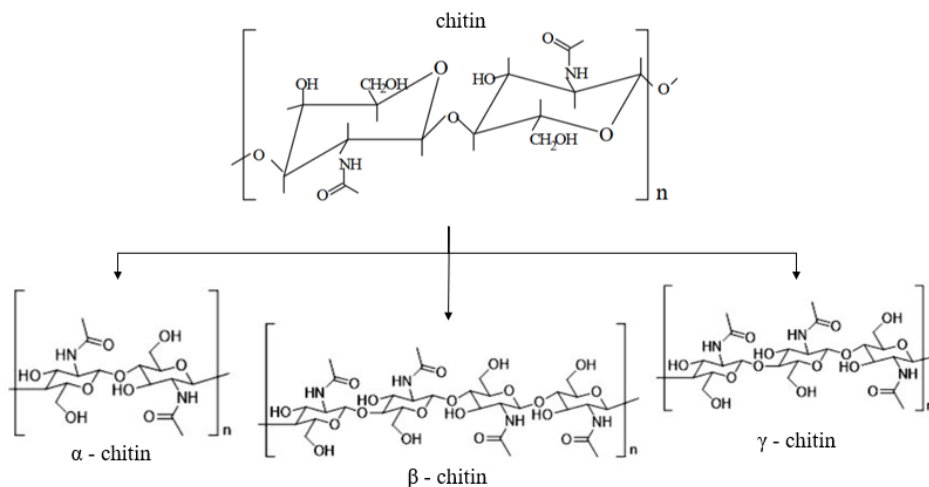


Figure 1. Polymeric forms of chitin.

Chitosan has a high affinity for adsorbing various contaminants (organic and inorganic) from aqueous solutions. This naturally occurring polymer is non-toxic, biocompatible, biodegradable, cheap, and hydrophilic [7, 8].

In this paper, the latest achievements (mainly from 2020 to 2025) in the utilisation of chitosan-based adsorbent in the elimination of organic and inorganic contaminants (such as metal ions and organic dyes) from aqueous solutions using the adsorption process have been presented. The effect of the modification process on the chitosan-based adsorbents'

sorption properties has been discussed. The main advantages and limitations of chitosan-based adsorbents were considered, including their regeneration method and impact on the environment.

2. Characteristic and Adsorption Properties of Chitosan-Based Adsorbents

The high adsorption capacity of chitosan is due to the presence of numerous reactive functional groups in its structure. The binding of metal ions by chitosan and chitosan-based adsorbents may result from chelation, electrostatic attraction, or an ion exchange mechanism in which pH plays a key role. The adsorption capacity of chitosan depends on its crystallinity, affinity for water, and degree of deacetylation. Most aqueous acids dissolve chitosan. Acids' protonation of the amino groups of chitosan creates many cationic sites, increasing its solubility (polarity increases). The amino groups of chitosan are responsible for chelation and binding to metal ions. Moreover, chitosan, as a polymer with cationic nature (pKa 6.2–7), is protonated in an acidic environment ($-\text{OH}$ and $-\text{NH}_2$ groups converted into $-\text{OH}_2^+$ and $-\text{NH}_3^+$), therefore it has an electrostatic charge that enables the sorption of nutrients such as phosphates or nitrates (e.g., NO_3^- and PO_4^{3-}). Chitosan can also adsorb anionic dyes and halogens due to the anion exchange mechanism. Moreover, $-\text{NH}_2$ and $-\text{OH}$ functional groups enable the adsorption of other pollutants such as phenol, antibiotics, and pesticides [9–13].

The adsorption capacity of chitosan and chitosan adsorbents depends on the degree of deacetylation, molecular weight, and crystallinity, i.e., the availability of amino groups. The degree of deacetylation of chitosan depends on the concentration and temperature applied during the chitin deacetylation process, with the sorption capacity increasing as the degree of deacetylation increases. Deacetylation is the process where the *N*-acetyl groups of chitin are chemically hydrolysed in acidic or alkaline conditions. Since low pH can potentially break the glycosidic bond, alkaline deacetylation is preferred. This process can occur at low temperatures (known as homogeneous deacetylation) or at high temperatures (referred to as heterogeneous deacetylation), depending on the product being produced. Furthermore, the increase in temperature allows the deacetylation process to be carried out in a shorter time [13–15]. The increase in chitosan concentration in the solution and the increase in the molecular weight reduce the degree of deacetylation and improve the adsorption kinetics (CS is then more hydrophobic). On the other hand, the higher the molecular weight of chitosan, the lower its solubility [16, 17]. Considering the properties of chitosan (Figure 2), especially its high crystallinity, low mechanical strength, and its solubility in an acidic environment, it cannot be directly used as an adsorbent; hence, its modifications are necessary [18].

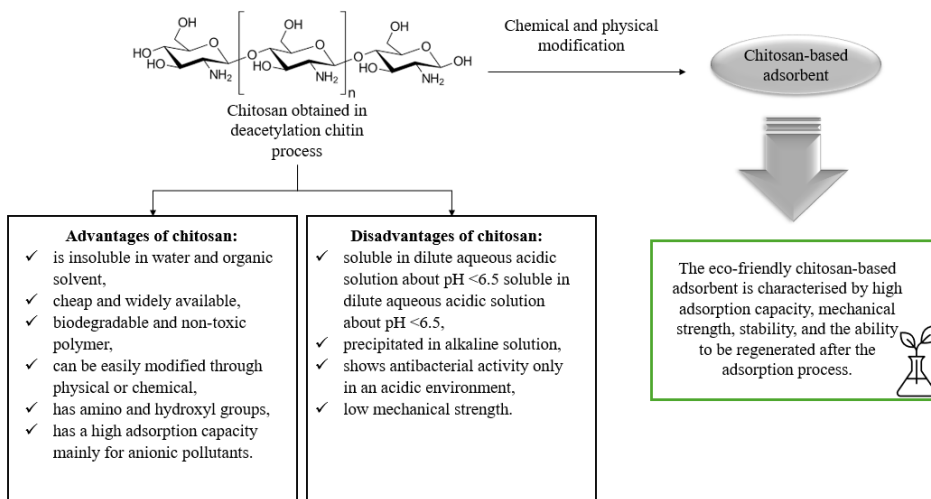


Figure 2. Advantages and disadvantages of chitosan [based on literature 19, 20].

3. Modification of Chitosan-Based Adsorbents

Chitosan-based adsorbents can be enhanced through physical and chemical modifications to improve their application properties. The different forms of chitosan, such as beads, powder, film, or nanofibers, are physically modified by blending and conversion. Chitosan composites obtained by mixing chitosan with other materials will exhibit better physical strength and adsorption performance, and their thermal and acid pH stability will increase [19]. Organic and inorganic fillers are used for this purpose. Organic fillers improve the adsorption properties of chitosan by forming hydrogen bonds with the amino group of the chitosan molecule, introducing additional active sites. Based on literature, chitosan blending with cellulose, carboxymethyl cellulose (CMC), polyacrylic acid (PAA), polyethylene oxide (PEO), and poly(vinyl alcohol) (PVA), etc., to form an organic-organic hybrid network. In addition, various inorganic compounds such as graphene oxide (GO), zeolite (Ze), fly ash (FA), etc., can enhance the adsorption properties of chitosan. While these inorganic fillers are stable, they often lack strength, making it challenging to modify their structure, size, shape, physical and chemical properties [11].

3.1. Physical Modification of Chitosan-Based Adsorbents

Chitosan adsorbents obtained by physical modification successfully remove organic dyes and metal compounds from aqueous solutions (Table 1). For example, chitosan-cellulose beads are used to remove Ni(II), Cu(II), and Cr(III) ions from wastewater [21], while the 3D porous bioadsorbents based on chitosan/alginate/cellulose nanofibers (CSA) can remove Eriochrome black-T (EBT) dye from aqueous solutions [22]. The chitosan-cellulose composite features a crystalline structure, while the chitosan-alginate composite has a three-dimensional, interconnected porous structure, making them potentially effective adsorbents [20, 21]. Tang *et al.* prepared a new chitosan composite that is grafted with polyacrylic acid and graphite oxide (CS-g-PAA/GO) to separate cationic dyes such as rhodamine 6G (R6G) and methyl violet (MV) from aqueous solution [23]. Another organic filler that improves the efficiency of adsorption of metal ions and organic dyes is

Table 1. Selected chitosan-based adsorbents obtained by physical modification and their application for removing of selected pollutants from aqueous solutions (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
Chitosan–cellulose beads	A chitosan solution in acetic acid (1% w/v) was blended with cellulose. The mixture was then added dropwise to the 10% NaOH solution to form chitosan-cellulose beads.	The adsorption efficiency depends on the large surface area of the adsorbent and the negative zeta potential (pH below 7.22, due to the presence of protonated NH_3^+ groups).	Ni^{2+} Cu^{2+} Cr^{3+}	99.80 mg/g 79.98 mg/g 99.10 mg/g	[21] 2020
CSA	A chitosan solution in acetic acid (2% w/v) was added dropwise into the sodium alginate (SA) solution. Next, an aqueous suspension of cellulose nanofibers (NFs) (15 wt.%) and SDS solution (1 wt. %), as a surfactant, was added to the CS/SA solution. The resulting mixture was dispersed using ultrasound.	The EBT removal efficiency using CSA increased significantly with the change of pH from 10 to 3, due to the change in electrostatic interactions between the adsorbate and the adsorbent.	EBT	2015 mg/g	[22] 2021
CS-g-PAA/GO	CS-g-PAA/GO composite was synthesised through solution intercalation graft copolymerisation involving CS, acrylic acid (AA), and GO. <i>N,N'</i> -methylenebisacrylamide (MBA) served as a cross-linking agent, while potassium persulfate (KPS) functioned as the initiator.	The small amount of GO affects the adsorption capacities. Between R6G and CS-g-PAA/GO, hydrogen bonds and electrostatic interactions occur, and in the case of MV, only electrostatic interactions occur.	R6G MV	224.6 mg/g 169.2 mg/g	[23] 2020

Table 1. (continued) Selected chitosan-based adsorbents obtained by physical modification and their application for removing of selected pollutants from aqueous solutions (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
CS-PVA	The membranes were created by mixing a chitosan solution in acetic acid with a PVA solution (CS/PVA membrane) or with a PVA solution that contains detonation nanodiamonds (DND) (CS/PVA-DND membrane).	The adsorption of Pb^{2+} ions onto CS-PVA-DND and CS-PVA occurs through the surface chelating mechanism. The addition of DND increases the sorption capacity. This is because the nanoparticles enhance surface porosity and improve affinity due to the functional groups on the DND surface.	Pb^{2+}	121.3 mg/g	[24] 2020
CS-PVA-DND				29.5 mg/g	
m-CS-PVA/FA	Fly ash microparticles were added to a magnetic CS and PVA polymer matrix to obtain the m-CS-PVA/FA composite.	The dye adsorption process likely occurs due to electrostatic attraction and other interactions, including dipole-dipole hydrogen bonding, Yoshida hydrogen bonding, and $n-\pi$ stacking.	RO16	123.8 mg/g	[25] 2021
CS/CMC-NCH	The GO nanosheets were functionalised with vinyltriethoxysilane (VTES) (grafting), which was used as a chemical crosslinker in the synthesis of CS and CMC for developing a CS/CMC-NH.	MB and MO's adsorption occurs due to electrostatic interactions and hydrogen bonding due to the presence of CS and CMC functional groups. Furthermore, the presence of GO in the CS/CMC-NCH structure allows to bind the dye through $\pi-\pi$ interactions.	MB MO	99% 82%	[26] 2021

Table 1. (continued) Selected chitosan-based adsorbents obtained by physical modification and their application for removing of selected pollutants from aqueous solutions (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
MCSGO	Chitosan dissolved in acetic acid was added to the GO suspension, and then spinel ferrites NPs CuFe ₂ O ₄ NPs were added. The reacting mixture was blended in an ultrasonic bath.	The adsorption of IC and SAF dyes onto MCSGO occurs due to electrostatic interactions, hydrogen bonding, and π - π interactions.	SAF IC	66.15 mg/g 112.6 mg/g	[27] 2023
GO@CS	The GO@CS composite beads were developed using continuous draping techniques in a 3% NaOH solution, with GO being incorporated into the CS solution containing acetic acid.	The adsorption efficiency increases with increasing pH of the environment, the binding sites become more ionised (the H ⁺ concentration will be reduced).	MB	23.26 mg/g	[28] 2022
GOH/DMCS	The hydroxylated graphene oxide (GOH) was modified through carboxylation, followed by the incorporation of diatomite (DE) and magnetic chitosan with Fe ₃ O ₄ (MCS) onto GOH by blending, resulting in GOH/DMCS.	The adsorption process of MB onto GOH/DMCS occurs as a result of electrostatic interaction, hydrogen bonding, van der Waals force, and π - π bonding.	MB	205.34 mg/g	[29] 2022
CS/GO/Fe	To a graphene oxide/iron(III) oxide hydroxide composite in deionised water, iron(II) sulfide was added while mixing in an ultrasonic bath, followed by the dropwise addition of hydrogen peroxide and a solution of CS in acetic acid	A monolayer adsorption mechanism was demonstrated through chelation with the functional groups of chitosan, surface oxide, and iron(III) hydroxide.	Cd ²⁺ Pb ²⁺	93.70% 82.91%	[30] 2021

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Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
CS-Ze	The mixture of CS in acetic acid and zeolite was added ECH as a cross-linking agent, then added dropwise to NaTPP solution, which is also a crosslinker.	A strong affinity was demonstrated between Pb^{2+} ions and the surface of the Ch-Z composite adsorbent (adsorption is energetically favourable).	Pb^{2+}	275 mg/g	[31] 2023
CS/Ze-A	CS/Z-A composite was developed; the mixture of CS in acetic acid and zeolite was subjected to stirring and sonication irradiation.	Physical adsorption occurred in the case of Cd^{2+} ion adsorption, while chemical adsorption was observed for As^{5+} ions.	Cd^{2+} As^{5+}	170 mg/g 125 mg/g	[32] 2022
CS/TGiG-NF	CS/TGiG-NF membrane was prepared using chitosan and 1,3,5-triglycidyl isocyanurate (TGIC) through a gradient cross-linking process on a polyethersulfone ultrafiltration membrane (PES).	Gradient cross-linking improves the stability (mechanical strength) of full cross-linking and improves membrane permeability while simultaneously separating salts.	Cu^{2+} Fe^{3+} Zn^{2+}	98.03% 99.04% 98.96%	[33] 2021

Table 1. (continued) Selected chitosan-based adsorbents obtained by physical modification and their application for removing of selected pollutants from aqueous solutions (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
NH ₂ -Ag-MOF@CSC	The NH ₂ -Ag-MOF/CS composite sponge was cross-linked using citric acid (citric acid was added to a solution containing NH ₂ -Ag-MOF and CS). The Ag-MOF was prepared by encapsulating sulfadoxine in a solution of AgNO ₃ dissolved in methanol with 2-methylimidazole.	The adsorption capacity decreased with increasing pH, because on the NH ₂ -Ag-MOF@CSC surface predominant -OH ions, which compete with chromium ions (CrO ₄ ²⁻) in solution.	Cr ⁶⁺	382.6 mg/g	[34] 2024
NI-CLCB	The acetic acid solutions containing 3CdSO ₄ ·8H ₂ O and chitosan, or raw chitosan, were mixed with sodium tripolyphosphate solution, forming II-CLCB or NI-CLCB composite.	The main adsorption mechanism was chemisorption. The amino and phosphate groups were the main bonding sites for Cd(II) ions.	Cd ²⁺	0.87 mmol/g	[35] 2022
II-CLCB	Sodium tripolyphosphate acted as the cross-linking agent.			1.05 mmol/g	
NaX/Ze-CS	The chitosan-NaX zeolite hybrid beads were prepared through an encapsulation process.	The removal percentage of Cu(II) ions decreases with increasing initial metal concentration due to the saturation of the adsorbent's surface with metal ions.	Cu ²⁺	217.81 mg/g	[36] 2023

Table 1. (continued) Selected chitosan-based adsorbents obtained by physical modification and their application for removing of selected pollutants from aqueous solutions (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
NCs Mg-CS-Ze	The composite was prepared by mixing a solution of CS in acetic acid with NiF at the appropriate concentration. NiF was produced by dissolving metal nitrates (Ni/Fe ratio 1:2) in distilled water, which results in the formation of Ni ₂ O ₄ through autocombustion.	The main factor of AR dye adhesion to the nanocomposite is electrostatic interactions. Moreover, the surface of MgF-CS-Ze NCs is highly protonated, which enhances the adsorption rate of the AR molecule.	AR	55.55 mg/g	[37] 2024
CS/Ze-DZC	The composite was obtained by mixing CS and Ze. The resulting mixture was washed with distilled water until a neutral pH was reached, referred to as DZC.	The adsorption phenomenon occurs probably due to the electrostatic force of attraction between the CS/Z composites and the dye molecules.	RO122	99.5%	[38] 2025
Y/CS/MFA	MFA was added to the CS solution. The resulting mixture was then added dropwise to a solution of yttrium nitrate. The Y/CS/MFA composite was obtained by drying, grinding, and sieving, resulting in particle sizes of less than 61 µm.	Dye adsorption depends on pH and is primarily influenced by the existing forms and functional groups of Y/CS/MFA and DG 6 in solution. Both physical and chemical adsorption can co-occur.	DG 6	616 mg/g	[39] 2020

Table 1. (continued) Selected chitosan-based adsorbents obtained by physical modification and their application for removing of selected pollutants from aqueous solutions (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
CS/FA/Fe ₃ O ₄	The magnetic CS-FA/Fe ₃ O ₄ beads were obtained by adding FeCl ₃ ·6H ₂ O and FeCl ₂ ·4H ₂ O to the CS and FA solution.	Based on the kinetic models and isotherms, it was found that the adsorption is influenced by chemisorption and a heterogeneous adsorption mode.	RO 16	73.1%	[40] 2020
Fe ₃ O ₄ @CTS/FA	Fe ₃ O ₄ @CTS/FA composite was prepared by mixing a CS, FA, and Fe ₃ O ₄ solution.	The adsorption onto Fe ₃ O ₄ @CTS/FA was based on electrostatic attraction, various H-bonding at multiple sites, and n-π bonding.	DB 86 DB 19	225 mg/g 199 mg/g	[41] 2024
CTS-ZFA-Fe ₃ O ₄	The composite was obtained by mixing the solution of CS and Ze in acetic acid with a mixture of FeCl ₃ ·6H ₂ O and FeSO ₄ ·7H ₂ O, which was dissolved in distilled water.	The arsenium adsorption mechanism is due to electrostatic interactions between As ⁵⁺ anions with OH ₂ ⁺ and NH ₃ ⁺ present on the adsorbent surface under low pH conditions.	As ⁵⁺	160μg/g	[42] 2024

poly (vinyl alcohol). For example, Vatanpour *et al.* prepared a chitosan/polyvinyl alcohol (CS/PVA) thin membrane incorporating detonation nanodiamonds (DNDs) as an adsorbent for Pb(II) ions [24]. In turn, a mixture of magnetic biocomposites made from chitosan, poly(vinyl alcohol), and fly ash (m-CS-PVA/FA) was utilised to remove reactive orange 16 (RO16) [25]. As mentioned, graphene oxide is successfully used as an inorganic filler to increase adsorption efficiency. Mittal *et al.* synthesised CS/CMC-NCH cross-linked nanocomposite hydrogels (NCH) with graphene oxide to remove organic dyes such as methylene blue (MB) and methyl orange (MO) [26]. Ahmed *et al.* obtained a magnetic nanocomposite of chitosan-graphene oxide decorated with copper ferrite (MCSGO) to remove safranin O (SAF) and indigo carmine (IC) dyes from wastewater [27]. Moreover, graphene oxide@chitosan (GO@CS) composite beads and the magnetic graphene oxide composite (GOH/DMCS) can eliminate methylene blue from aqueous solution [28, 29]. Other heavy metal ions (e.g., Pb and Cd) can be removed from aqueous solution using chitosan cross-linked into graphene oxide/iron(III) oxide hydroxide (CS/GO/Fe) nanocomposites [30].

Furthermore, the cross-linked chitosan-zeolite composite adsorbent and chitosan/zeolite-A hybrid composite (CS/Ze-A) can be used for efficient removal of toxic metal ions such as Pb^{2+} , Cd^{2+} , and As^{5+} from aqueous solutions [31, 32]. The cross-linking of chitosan enhances its stability and mechanical strength, while incorporating zeolite into the chitosan-based adsorbent provides additional surface area and active sites for the adsorption of Pb(II) ions [31]. The CS/TGIG-NF membrane modified by ionic cross-linking (using sodium dodecyl sulfonate, SDS, and triglycidyl isocyanurate, TGIC) enables the removal of divalent salts and heavy metal ions such as CuCl_2 , FeCl_3 , and ZnCl_2 . The membranes were prepared in a gradient cross-linking process, which improves the composite's mechanical strength and permeability while ensuring salt retention [33]. The NH_2 -Ag-MOF@CSC composite sponge cross-linked with citric acid can effectively remove chromium ions from aqueous solutions. The NH_2 -Ag-MOF@CSC composite possesses a significantly larger specific surface area than pure chitosan microspheres, making it an effective adsorbent for metal ions [34]. Moreover, Babakhani and Sartaj used cross-linked chitosan beads containing sodium tripolyphosphate with an ionic imprint (II-CLCB) and without an ionic imprint (NI-CLCB) for biosorption of cadmium(II) ions. The adsorption on a porous adsorbent is usually a multi-step process. During the first stage of adsorption, which occurs in the boundary layer or as a result of external diffusion, the process occurred more rapidly with the NI-CLCB composite. However, in the second stage, involving metal diffusion within the pores, the adsorption process was quicker for the II-CLCB composite. Due to cross-linking, metal ions have more difficulty accessing the active sites of NI-CLCB, unlike II-CLCB, which features mesopores on its surface. [35].

The NaX zeolite and chitosan hybrid composite (NaX/Ze-CS) can be used to remove copper(II) ions [36], and a nanocomposite consisting of MgFe_2O_4 -chitosan-ZSM-5 zeolite (NCs MgF-CS-Ze) or chitosan/zeolite (CS/Ze-DZC) composites can be used to remove acid red (AR) and reactive orange 122 (RO122) from aqueous solutions, respectively [37, 38]. Organic fillers such as zeolite improve chitosan-based adsorbent properties. Mazouz *et al.* found that increasing the zeolite content in the beads affects the efficiency of Cu(II) ion removal. Because the adsorption of Cu(II) ions onto zeolites occurs through ion exchange, the pH of the solution influences the adsorption by the competition between the hydrogen cations H^+ and the copper Cu(II) cations on the available surface [36]. Additionally, it is believed that filling chitosan with zeolite enables the production of a composite material with better thermal and mechanical stability. Adding ferrites to the zeolite-chitosan composite enhances the adsorbent's ability to separate from water, thus facilitating its regeneration [37]. Moreover, chitosan modified with fly ash can effectively

adsorb selected organic dyes and metal ions from an aqueous solution. Li and Ren developed a new adsorbent (Y/CS/MFA) consisting of a small amount of CS and Y^{3+} ions, which were doped onto acid-modified fly ash (referred to as MFA) to remove direct green 6 (DG 6). The adsorption capacity of the Y/CS/MFA composite is much higher than that of raw FA, Y/MFA, and CS/MFA composites. Because the Y/CS/MFA composite consists of inorganic matter, rare earth elements, and organic compounds, the removal efficiency of DG 6 dye was close to 100%. Y/CS/MFA can simultaneously play the role of bridging, chelating, and neutralising adsorption in the adsorption process of DG 6 [39]. Magnetic chitosan-fly ash adsorbents, such as CS/FA/Fe₃O₄ and Fe₃O₄@CTS/FA, effectively remove reactive orange 16, direct blue 86 (DB 86), and direct black 19 (DB 19) dyes from aqueous solutions, respectively [40, 41]. The results indicate that a strong electrostatic interaction between the protonated amino ($-NH_3^+$) functional group of CS-FA/Fe₃O₄ composite and sulfonate ($-SO_3^-$) groups of the RO16 dye affects the growth of the RO16 dye removal [40]. Electrostatic adsorption was identified as the primary interaction between anionic dyes (DB 86 and DB 19) and Fe₃O₄@CTS/FA [41]. Tran *et al.* used the CTS-ZFA-Fe₃O₄ adsorbent to remove As⁵⁺ ions from water. In an acidic environment, the adsorption of arsenic (V) ions onto the composite occurred due to electrostatic interaction between adsorb metal ions and $-OH_2^+$ and $-NH_3^+$ groups which exist on the CTS-ZFA-Fe₃O₄ surface (at low pH, the protonation of the amino group on the composite increases) [42].

3.2. Chemical Modification of Chitosan-Based Adsorbents

Because chitosan contains an amine group, it can be successfully chemically modified through various reactions, such as alkylation, acylation, quaternisation, carboxyalkylation, phosphorylation, sulfation, and grafting. The presence of hydroxyl groups in chitosan enables modification by reactions such as *O*-acetylation, hydrogen bonding with polar atoms, cross-linking, grafting, etc. (Table 2) [43, 44].

Grafting chitosan improves its antibacterial, chelating, and complexation properties [45]. Graft polymerisation allows the modification of the surface of a material by mixing two or more polymers. Grafting causes a change in the type and number of functional groups on the chitosan surface, which increases active adsorption sites. In the grafting process, an initiator system is often applied: Fenton's reagent, ferrous ammonium sulphate, ceric ammonium nitrate, ammonium and potassium persulphate, potassium diperiodatocuprate, and also enzymes and γ -irradiation [44, 46–48]. Grafting modifications to chitosan enables more effective removal of organic dyes (e.g., acid red 27 (AR27), acid blue 83 (AB 83), etc.) and metal ions (e.g., As³⁺) from aqueous solutions.

Enhanced antimicrobial and antifungal properties of chitosan can be achieved through the quaternisation process, which involves introducing a quaternary ammonium group into the biopolymer backbone [44, 49]. Chitosan quaternisation occurs on side groups without disturbing the main CS skeleton (the material gains additional properties while maintaining physicochemical and biological properties). As a result, a positive charge is generated onto chitosan (leading to electrostatic repulsion between chitosan chains), with the grafting of lateral alkyl chains [50]. Quaternisation enables the removal of a wide range of contaminants such as organic dyes (e.g., Congo red (CR)), heparin, or high-molecular-weight invert sugar alkaline degradation products (HISADPs).

The carboxylation process (introduction of carboxyl groups to chitosan) significantly improves the water solubility of chitosan, its biocompatibility, as well as its flocculating, antibacterial, thickening and film-forming properties. The carboxylation reaction can occur with either the hydroxyl or amino groups present in the chitosan molecule, whether individually or together. Most commonly used for this purpose is glyoxylic acid, which

Table 2. Examples of various chitosan-based adsorbents used to remove selected contaminants from aqueous solution (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
Sulphydryl-functionalised chitosan (CS-SH)	grafting: Hydroxysilane (3-mercaptopropyltrimethoxysilane) was grafted onto chitosan by a condensation reaction.	A monolayer chemisorption mechanism onto the homogeneous surface of CS-SH was observed. The presence of coexisting ions did not affect arsenic removal.	As ³⁺	99%	[51] 2021
Grafted and crosslinked chitosan beads (CS-PEI-GLA)	Grafting and cross-linking: The adsorbent was synthesized using microwave radiation without a radical initiator or catalyst. Then the grafted CS was stabilized by cross-linking with glutaraldehyde (GLA).	CS-PEI-GLA enables the adsorption of the anionic AR27 dye. At a pH of 8.4, the positively charged ammonium groups (protonated primary/secondary amine groups, NRH ₂ ⁺) on the surface of CS-PEI-GLA facilitate the adsorption of the anionic dye AR27.	AR27	48 mg/g	[47] 2020
Grafted chitosan with kaolin CS-g-PAA	Grafting: The CS-g-PAA was prepared by ultrasonically initiated polymerization using acrylamide (AM), 3-acrylamidepropyl-trimethylammonium (AATPAC) and CS as monomers.	The separation of AB 83 onto CTS-g-PAA occurred due to adsorption and flocculation, which resulted from electrostatic interactions.	AB 83	91.9%	[48] 2020

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Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
Quaternary-ammonium-functionalised magnetic chitosan microspheres (IQMCM)	Quaternisation and cross-linking: Chitosan was coated with magnetic particles (Fe ₃ O ₄) using the emulsion cross-linking method. Quaternisation was then performed by adding NaI in anhydrous methanol.	A monolayer chemisorption mechanism onto IQMCM was by electrostatic attraction, hydrogen bonding, and intraparticle diffusion interactions.	CR	630.21 mg/g	[52] 2022
Quaternary chitosan nanoparticles (QFCNs)	Fe ₃ O ₄ produced functionalised nanoparticles (FCNs), which were then subjected to a quaternisation reaction with glycidyltrimethylammonium chloride (GTMAC).	The adsorption of heparin onto QCNFs occurred as a result of the electrostatic interaction between the -N(CH ₃) ₃ ⁺ groups of QCNFs and the -OSO ₃ ⁻ , -NHSO ₃ ⁻ , and -COO ⁻ groups of heparin.	Heparin	33.04 mg/g	[53] 2025
Quaternary ammonium-functionalized magnetic chitosan microspheres (QAMCM)	Quaternisation and cross-linking: Chitosan was coated with magnetic particles (Fe ₃ O ₄) using the emulsion cross-linking method. Quaternisation was then performed by (3-chloro-2-hydroxypropyl)trimethylammonium chloride.	The adsorption process onto AQMCM resulted from chemisorption involving electrostatic attraction and electron sharing.	HISADP	98.03 mg/g	[54] 2021

Table 2. (continued) Examples of various chitosan-based adsorbents used to remove selected contaminants from aqueous solution (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
Chitosan-based adsorbent modified with quaternary ammonium group (ZIF-8/CS-N)	Quaternisation: ZIF-8/chitosan was synthesised via co-precipitation modification and in situ synthesis. In ZIF-8/CS-N adsorbent: Zn is associated with a 2-methylimidazole (Im) bridge to form the M–Im–M network in ZIF-8. Quaternisation was performed by 2-[(methacryloyloxy)ethyl] trimethyl ammonium chloride solution.	The adsorption onto ZIF-8/CS-N occurred with an electrostatic interaction and chelation between chitosan and metal ions.	As ⁵⁺	54.2 mg/g	[55] 2023
Carboxylated chitosan/ carboxylated nanocellulose (CYCS/CNC) hydrogel beads	Carboxylation and cross-linking: The cross-linking process was carried out by mixing carboxylated chitosan (CYCS) and carboxylated nanocellulose (CNC) in a ratio of 4:1.	A monolayer adsorption of Pb(II) ions occurs as a result of electrostatic interactions between metal ions and carboxyl groups onto the CYCS/CNC composite.	Pb ²⁺	334.92 mg/g	[56] 2021

Table 2. (continued) Examples of various chitosan-based adsorbents used to remove selected contaminants from aqueous solution (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
CS-DTPA/PEO NF	<p>Carboxylation: The chitosan-DTPA/polyethylene oxide nanofibers (CS-DTPA/PEO NFs) were prepared using EDC/NHS crosslinking in a <i>N,N,N',N'</i>-tetramethylethylenediamine TEMED buffer, which prevents the formation of insoluble chitosan. CS-DTPA/PEO NFs were produced by electrospinning. Carboxylation was performed by diethylenetriaminepentaacetic acid (DTPA).</p>	<p>The removal of metal ions occurs due to the electrostatic attraction between the metal ions and the -OH and -NH₂ groups present in the chitosan fragments, and from the coordination of divalent metals with DTPA fragments and chitosan NH₂ groups and also results from the leaching of K or Na ions from two anions carboxylate fragments of DTPA.</p>	<p>Cu²⁺ Pb²⁺ Ni²⁺</p>	<p>177 mg/g 142 mg/g 56 mg/g</p>	<p>[57] 2020</p>
MCS-PAA	<p>Carboxylation and cross-linking: Magnetic nanocomposite CS-PAA was prepared using a solvothermal method with GLA as a cross-linking agent in the presence of chitosan and Fe₃O₄. Polyacrylic acid (PAAA) was activated by 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDC) and <i>N</i>-hydroxysuccinimide (NHS).</p>	<p>Chemical adsorption, specifically the complexation between carboxyl, amino, and hydroxyl groups in MCS-PAA and Pb²⁺, was observed.</p>	<p>Pb²⁺</p>	<p>204.89 mg/g</p>	<p>[58] 2020</p>

Table 2. (continued) Examples of various chitosan-based adsorbents used to remove selected contaminants from aqueous solution (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
Chitosan modified with carboxyl groups (CTS-CAA)	Carboxylation and cross-linking: cross-linking with GLA. The next reaction was with epichlorohydrin (CTS-EC), followed by diethylene triamine (CTS-DET), and finally, carboxylation was conducted using monochloroacetic acid (CTS-CAA).	The adsorption onto CTA-CAA occurred with the reaction chelation between the -COO group on chitosan and Zn(II) and Cu(II) ions.	Cu ²⁺ Zn ²⁺	3.47 mmol/g 1.89 mmol/g	[59] 2022
SBMGO	The Schiff base was functionalised with GO, then Fe ₃ O ₄ nanoparticles (in an ultrasonicated bath). The Schiff base was obtained by adding to CS in acetic acid 0.9 g of the 3-(p-anisyl)-4-formylsydnone (P-AnFO).	The anionic charges in the Schiff base and GO help bind metal ions by electrostatic forces. The presence of GO increases the adsorption capacity due to the increased surface area of the adsorbent.	Cu ²⁺ Cr ⁶⁺	111.11 mg/g 142.85 mg/g	[60] 2020
Magnetic phosphorylated chitosan composite (P-MCS)	Phosphorylation: Chitosan was coated with magnetic particles Fe ₃ O ₄ and functionalised by anchoring phosphate (ortho-phosphoric acid).	Adsorption of Co(II) ions occurred through electrostatic repulsion of metal ions at low pH onto protonated chitosan and the chelation between the functional groups of the composite and the metal ions.	Co ²⁺	46.1 mg/g	[61] 2020

Table 2. (continued) Examples of various chitosan-based adsorbents used to remove selected contaminants from aqueous solution (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
Chitosan-based adsorbent with functional groups: phosphoric acid, amidoxime, and quaternary ammonium groups (PACNC)	Phosphorylation, nitrile formation, quaternisation and amidoximation: After phosphorylation with phosphorus pentoxide, the following chemical reactions were conducted: nitrile formation, quaternisation, and amidoximation. The product obtained was then combined with a mixture of chitosan and ethyl acid, along with an aqueous solution of phosphated chitosan with the addition of EPI.	The adsorption resulted from the synergistic effect of amidoxime, phosphate, hydroxyl, and ammonium groups on PACNC, forming a complex with UO_2^{2+} .	U^{6+}	962.226 mg/g	[62] 2023
Phosphorylated chitosan (P-CS)	Phosphorylation: Phosphorylating chitosan in 6% H_3PO_4 solution.	The adsorption mechanism was based on electrostatic attraction, H-bonding, and n- π interaction between the adsorbent and AR 88 dye.	AR 88	230 mg/g	[63] 2021
Alkylated chitosan with a quaternary ammonium group (Ch-QAG)	Alkylation: <i>N</i> -alkylated chitosan was obtained using the liquid phase polymer retention (LPR) coupling method. <i>N</i> -(3-chloro-2-hydroxypropyl) trimethylammonium chloride (CHTAC) was used as an alkylation agent.	Adsorption occurs due to ion exchange between chloride counterions of quaternary ammonium groups (CHTAC composite) and arsenate ions in the solution.	As^{5+}	80%	[64] 2020

Table 2. (continued) Examples of various chitosan-based adsorbents used to remove selected contaminants from aqueous solution (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
Chitosan-based sponges (CS-SP)	Acylation: <i>N</i> -acylation reaction of chitosan with various fatty acids (C6–C16) chlorides, such as hexanoyl chloride, heptanoyl chloride, octanoyl chloride, or nonanoyl chloride.	Chitosan-based sponges containing longer-chain fatty acid chlorides showed higher adsorption efficiency due to the increased hydrophobicity of the sponge.	MO	380 mg/g	[65] 2024
<i>N</i> -Alkylated Chitosan (N-CS)	Alkylation: Deacetylated chitosan was subjected to an <i>N</i> -acetylation reaction using CHTAC.	Adsorption occurred mainly through electrostatic interaction between <i>N</i> -alkylated chitosan-adsorbent and NA in a pH above 5.95. The presence of aromatic groups in N-CS improves the adsorption capacity.	NA	561.51 mg/g	[66] 2023
Zwitterionic polymeric nanocomposite (PNs-HTC)	PNs-HTC were synthesised using alkylated ionic chitosan macromonomers and ionic monomers linked to hydroxalate (HTC) through in situ free radical polymerisation. CHTAC was used as the alkylating agent and glycidyl methacrylate (GMA) as the source of vinyl groups.	The modified structure of PNs-HTC facilitated ion exchange and electrostatic attraction between oppositely charged functional groups of CIP. Moreover, the increase in ionic strength hinders the effective adsorption of CIP.	CIP	84.43 mg/g	[67] 2025

Table 2. (continued) Examples of various chitosan-based adsorbents used to remove selected contaminants from aqueous solution (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
Caproyl chitosan (C-CS)	Acylation: Chitosan acetylated was obtained with caproyl chloride or palmitoyl chloride in various acyl chloride: chitosan mass ratios.	The longer acyl chain of palmitoyl enhances hydrophobic interactions, providing higher adsorption efficiency and higher stability of the polymer, unlike the use of caproyl (shorter acyl chain, weak hydrophobic interaction).	PO ₄ ³⁻	63%	[68] 2019
Palmitoyl chitosan (P-CS)			PO ₄ ³⁻	71%	
Chitosan-based adsorbent on Schiff Bases-g-poly (acrylonitrile) (Ch-g-Sch I)	Grafting and alkylation: In the first stage, the grafting (acrylonitrile) process was carried out, and then the obtained product was alkylated with appropriate Schiff bases (Sch I and Sch II). Schiff bases I and II contain salicylaldehyde and p-anisaldehyde, respectively, as alkylation agents.	The hydroxyl group showed less activity toward metal ions. After modification of the Schiff base, accumulated layers with small, distributed pores are observed on the surface of the adsorbent.	Cu ²⁺	51.61 mg/g	[69] 2022
Chitosan-based adsorbent on Schiff Bases-g-poly (acrylonitrile) Ch-g-Sch II			Cr ³⁺	52.96 mg/g	
			Cd ²⁺	183.78 mg/g	
		The methoxy group showed a greater activity toward metal ions. After modification of the Schiff base, accumulated layers with larger, distributed pores are observed on the surface of the adsorbent.	Cu ²⁺	337.12 mg/g	
			Cr ³⁺	98.88 mg/g	
			Cd ²⁺	322.92 mg/g	

Table 2. (continued) Examples of various chitosan-based adsorbents used to remove selected contaminants from aqueous solution (years 2020–2025).

Chitosan-based adsorbent	Method of adsorbent formation	The main information about the adsorption process	Pollution removed	Removal efficiency	[Ref] Year
<p>Porous chitosan materials (PCM)</p>	<p>Cross-linking and alkylation: The adsorbent was prepared by freezing the cross-linked chitosan with GLA to form cryogels, and then reducing them with NaBH4 to convert the C=N bonds into C-N bonds.</p>	<p>A monolayer of chemisorption was observed, with the adsorption sites uniformly distributed across the surface of the PCM.</p>	<p>Cu²⁺ CR</p>	<p>88.73 mg/g 3261.05 mg/g</p>	<p>[70] 2024</p>
<p>Crosslinked chitosan-genipin with algae (CTS-GEN/AGA)</p>	<p>Cross-linking: A polymer matrix consisting of chitosan and algae (mixture) was modified using a cross-linking method with genipin in a hydrothermal process.</p>	<p>The adsorption mechanism was based on three main interactions: electrostatic interactions, hydrogen bonding, and n-π bonding interactions.</p>	<p>MV</p>	<p>76.49%</p>	<p>[71] 2025</p>

can directly oxidize the hydroxyl groups of chitosan to carboxyl groups, or chloroacetic acid, which can react with C₂-NH₂ and C₆-NH₂ on chitosan to form *N,O*-carboxymethyl chitosan [40, 51–52]. The latest studies report that modified chitosan, as a result of the carboxylation reaction, enables the effective separation of divalent metal ions such as copper, zinc and lead.

Furthermore, the alkylation process increases the solubility of chitosan by weakening the intermolecular hydrogen bonds. The solubility of the chitosan derivative can be controlled by the length of the alkyl chain of the introduced derivative (since the alkyl group is hydrophobic). Depending on where the alkyl group is introduced, chitosan molecules are distinguished as *N*-alkylation (the reaction takes place in the C₂-NH₂ group of chitosan) and *O*-alkylation (the reaction takes place in the C₆-OH or C₃-OH group acid derivatives, i.e., acid anhydrides and acid halides, are used as acylating agents). A distinction is made between *O*-, *N*- or *N,O*-acylation. *N*-acylation takes place in the amino group, *O*-acylation in the hydroxyl group, and *N,O*-acylation takes place simultaneously in the OH and NH₂ groups. As with carboxylation and alkylation, the course of the acylation reaction depends on the type of acylating agents used. *N*-acylation of chitosan (the reaction usually takes place preferentially at C₂-NH₂) improves its solubility in water, while *O*-acylated chitosan is more soluble in fats and is used to create stable, hydrophobic materials [72]. Adsorbents prepared in this way can be used to remove metal ions (e.g., Cu²⁺, Cd²⁺, and Cr³⁺), dyes (e.g., methyl orange, congo red), or pharmaceuticals (e.g., Ciprofloxacin (CIP) or nalidixic acid (NA)) from aqueous solutions. On the other hand, introducing anionic phosphate groups into chitosan results in an amphoteric polyelectrolyte that contains cationic amino groups. This modification significantly enhances the material's ability to exhibit both positive and negative charges across a wide pH range [63]. Therefore, the obtained sorption materials are successfully used to remove both metal ions (e.g., Co²⁺, U⁶⁺) and organic dyes (e.g. Acid Red 88 (AR 88)) from aqueous solutions.

Considering the low strength, possibility of regeneration, and reuse of chitosan adsorbents, they are subjected to a modification process. For this purpose, the cross-linking method is commonly used and frequently employed, typically alongside other modification techniques. Cross-linking agents (e.g., glutaraldehyde, epichlorohydrin, genipin, etc.), which contain at least two functional groups in their molecules, act as bridges between polymer chains by connecting to the functional groups of chitosan. This process allows linear chitosan particles to form a three-dimensional network structure resistant to water dissolution [11, 18].

Table 2 presents information summarising the capabilities of chitosan-based adsorbents obtained by various chemical modifications and intended to remove contaminants from aqueous solutions.

4. Recovery, Regeneration, and Reusability of Chitosan-Based Adsorbents

The essential feature of a good adsorbent is its ability to be reused and recovered, thanks to which the costs associated with its production can be significantly minimised. Spent adsorbents can be recovered and regenerated using magnetic separation, filtration, thermal desorption, solvent regeneration, microwave irradiation, supercritical fluid regeneration, advanced oxidation, and microbiologically assisted regeneration [75 and references therein]. In the case of chitosan-based adsorbent, chemical, biological, and thermal regeneration is used. The main limitations during the regeneration of chitosan-based adsorbent include its low mechanical stability, low chemical stability, and biodegradability. Moreover, chitosan decomposes at high temperatures and biodegrades in

contact with microorganisms due to the presence of oxidisable or hydrolysable bonds in its skeleton [9]. The macromolecular structure of chitosan and its many active spots enable a high adsorption capacity for pollutants. After the sorption process, chitosan-based adsorbents become saturated, toxic, and hardly biodegradable, and the bound pollutants can be washed out into the environment. Therefore, they must undergo a regeneration process before disposal and release into the environment [8]. Regeneration is carried out to remove adsorbed substances (solute or ion exchanger) by chemical treatment with mineral acids (H_2SO_4 , HCl and HNO_3), salts (NaCl , KNO_3 , Na_2CO_3 , Na_2SO_4), bases (NaOH , NH_4OH), complexing or chelating compounds (EDTA , Na_2EDTA) or a solution of organic acid (citric acid) and water [76, 77]. Thermal and biological desorption methods are not recommended because chitosan is not resistant to high temperatures and is also easily biodegraded in the presence of microorganisms [76]. Cationic dyes' desorption occurs when the solution's pH is lowered (then protonation of the adsorbent functional groups occurs), therefore, acidic desorbing solutions are commonly used to regenerate chitosan adsorbents. A chlorodihydrogen acid solution is most commonly used for this purpose because chloride anions from HCl can also form complexes with cationic dye molecules, and the resulting uncharged complex is released in the solutions [78]. Kim *et al.* carried out the regeneration of carboxymethyl chitosan-modified magnetic-cored dendrimers (CCMDs) after the adsorption of methylene blue (MB) using 0.1 M HCl ($\text{pH}=2$) in five consecutive recycling cycles. The desorption efficiency of MB was more than 99% [79]. Zeng *et al.* regenerated granular chitosan adsorbent (GA) in an alkaline solution (NaOH), as a result of which the bound arsenic (V) was transferred to the solid phase of the leaching solution. It has been proven that NaOH can be successfully used to wash As(V) ions from the adsorption column without destroying the adsorption properties of GA. Maximum arsenic desorption was demonstrated after approximately 4 hours and total desorption after approximately 14 hours [77]. Furthermore, Kwok *et al.* carried out the natural desorption of arsenic from chitosan flakes using a smaller amount of unbuffered water instead of a sodium hydroxide solution. The main advantage is the virtually zero cost of the desorption process, and the recovered chitosan can be successfully recovered and reused in separation processes. In addition, the concentrated arsenic solution can be reused in technological processes [80]. Da Silva Bruckman *et al.* investigated the separation efficiency of a chitosan-based magnetic adsorbent ($\text{CS}\cdot\text{Fe}_3\text{O}_4$) for ivermectin from an aqueous solution using NaOH and EtOH as desorbents. It was shown that ethanol enables higher regeneration and reuse efficiency, even after five consecutive sorption-desorption processes, than sodium hydroxide. This was probably due to the good solubility of the adsorbed antibiotic in EtOH . In contrast, NaOH proved effective up to the third sorption-desorption cycle, probably due to a change in the surface of the adsorbent [81]. In turn, Mao *et al.* used the Pd(II) ion-imprinted chitosan fibre (ICF) and the non-imprinted chitosan fibre (NICF) to separate metal ions from acidic solutions and also carried out a two-step desorption process for the selective removal of Pd(II) from solutions containing the interfering metals such as Co^{2+} , Ni^{2+} , Cu^{2+} and Pt^{4+} ions. It was found that two-step desorption during 1 M NaOH solution and 0.25 M thiourea dissolved in 0.5 M hydrochloric acid can be an efficient regeneration process in the selective desorption of Pd^{2+} from ICF adsorbent. It was confirmed that the two-step desorption process enables the selective separation of platinum group metal ions from acidic solutions. In the first desorption step, NaOH was used to wash out approximately 43.3% and 64.4% of Pt^{4+} ions from NIF and ICF, respectively. In the second desorption step, 86.5% of Pd^{2+} ions and 13.5% of Pt^{4+} ions were desorbed using acidified thiourea as an adsorbent (NICF), and 95.4% of Pd^{2+} ions and 4.6% of Pt^{4+} ions were desorbed using ICF as an adsorbent [82]. Vijayalakshmi *et al.* performed a desorption process (during 0.1 M HCl solution) from nanochitosan (NCS)/sodium alginate(SA)/microcrystalline cellulose

(MC) beads, which were used to remove Pb(II) ions from aqueous solution. After the first sorption-desorption process, 75.10% of lead(II) ions were released into the chloride solution, while after the second process, 65.10% were released. The re-adsorption capacity of the tested metal ions was 97.38% and 93.07%, after the first and second sorption-desorption cycles, respectively. The lower efficiency of the desorption process may be caused by blocking some active sites and changes in the chemistry and structure of the obtained NCS/SA/MC biosorbent. The process of releasing lead(II) ions from the chitosan adsorbent into an aqueous hydrochloric acid solution occurs as a result of ion exchange [83]. Maity and Ren used a composite adsorbent (Cs-PMA-HNT) made from chitosan with cross-linked polymethacrylic acid (PMA) and nanoscale halloysite nanotubes (HNT) to remove lead(II) and cadmium(II) ions from aqueous solutions. Five consecutive sorption-desorption processes were carried out using 0.1 M Na₂EDTA and 0.1 M HNO₃ as eluents. It was shown that HNO₃ better desorbed Cd²⁺ ions and EDTA Pb(II) ions. The tests showed that after the first sorption-desorption cycle, 98% of Pb²⁺ ions and 88% of Cd(II) ions were recovered using EDTA, and 90% of Pb²⁺ ions and 95% of Cd²⁺ ions using HNO₃. After five sorption-desorption cycles, 86% and 71% of lead(II) ions were removed using EDTA and HNO₃, respectively, and 86% and 71% of cadmium(II) ions were removed using EDTA and HNO₃, respectively. Strong electrostatic interactions between the metal ions and the adsorbent surface were found, and there was an absence of any irreversible changes on the adsorbent [84]. As stated above, chitosan adsorbents can be regenerated using salt solutions. Gao *et al.* compared the regeneration process of chitosan cross-linked zeolite molecular sieve (CTS/ZMS) used to remove nitrates from contaminated water with a 1 M solution of Na₂CO₃ and NaCl and a 1 M solutions of HCl and NaOH. The regeneration rate of CTS/ZMS when exposed to Na₂CO₃, HCl, NaCl, and NaOH solutions was 83.7%, 25.33%, 11.33% and 2.0%, respectively. The relatively low nitrate removal rate with HCl, NaCl and NaOH solutions was due to irreversible damage to the CTS/ZMS adsorption sites caused by the chloride and hydroxyl groups of the eluents. After five consecutive sorption-desorption cycles using Na₂CO₃ as a desorbing solution, the sorption capacity of CTS/ZMS decreased from 1.768 to 1.534 mg/g. Due to its low price and regeneration efficiency, Na₂CO₃ can be successfully used as a desorbing agent for chitosan adsorbents [85]. In turn, Liu *et al.* compared the regeneration process of chitosan-derived magnetic nanomaterial (CS-FeO) using NaOH, Na₂SO₄ and NaCl solutions against nitrite adsorption. The most effective eluent was the Na₂SO₄ solution, because after 5 times of regeneration (adsorption rate was approximately 55%) with this salt, no decrease in the adsorption rate was observed between each regeneration, and the adsorption of nitrite by CS-FeO with Na₂SO₄ as the eluent was still significantly higher than with NaOH or NaCl as the eluents. In addition, a new type of nanomaterial was synthesised by grafting porphyrin onto FeO, the removal rate of which was 80% after 5-fold regeneration with NaOH and after 5-fold regeneration with HCl, 85%, probably because both porphyrin and anthracite are involved in the adsorption of nitrite (surface adsorption) [86].

Regenerating adsorbents is crucial for both environmental and economic reasons. This process helps to reduce pollution and the costs involved in synthesising new sorption materials. Moreover, the regeneration process reduces the amount of sorption materials produced. During the chemical regeneration of chitosan, diluted aqueous solutions of acids, bases, and inorganic salts are utilised, which should not significantly harm the environment. Additionally, these solutions can be reused multiple times.

5. Summary

In obtaining adsorbents, special notice should be paid to their structure, sorption capacity, chemical and mechanical stability, and the possibility of reuse, biodegradability, or low production cost [87]. Despite the many advantages of chitosan, particularly its chemical structure, i.e., the presence of functional groups that favour the adsorption process and the possibility of obtaining it from natural shell waste, its use in its pure form is ineffective. Pure chitosan is mechanically unstable, highly crystalline, and dissolves in acidic aqueous solutions, which is why it undergoes a modification process. Currently, chitosan adsorbents obtained through chemical and physical modifications are of great interest to scientists and are mainly used to remove metals and their compounds, as well as organic dyes from water and wastewater, as well as pharmaceuticals in municipal wastewater.

This review presents detailed information on the adsorption capacity of chitosan-based adsorbents and explains that the modified adsorbents show high sorption capacity to remove various contaminants. In addition, the paper presents a method of regeneration of the used chitosan adsorbents, including the possibility of their reuse in the next sorption-desorption process. However, despite numerous reports in the literature, there is still no comprehensive understanding of the sustainable management of used adsorbents, which often contain toxic pollutants. The chitosan-based adsorbents presented in this paper prove that it is necessary to develop cheap, environmentally friendly adsorbents with a high sorption capacity for specific pollutants. In conclusion, chitosan adsorbents show great adsorption potential not only for removing pollutants but also for recovering valuable metals from aqueous solutions. The extraction of chitosan from waste and the use of modified chitosan adsorbents are not only economically beneficial but also environmentally friendly and in line with the idea of sustainable development.

6. References

- [1] Sen TK; (2023) Agricultural solid wastes based adsorbent materials in the remediation of heavy metal ions from water and wastewater by adsorption: a review. *Molecules* 28(14), 5575. **DOI:** 10.3390/molecules28145575
- [2] Selim MM, Tounsi A, Gomaa H, Hu N, Shenashen M; (2024) Addressing emerging contaminants in wastewater: Insights from adsorption isotherms and adsorbents: A comprehensive review. *Alex Eng J* 100, 61–71. **DOI:** 10.1016/j.aej.2024.05.022
- [3] Hou B, Yang X, Wang L, Shi T, Akram M, Wang L, Wan J, Gao B, Pan J; (2024) Fe doping enhanced Cr(VI) adsorption efficiency of cerium-based adsorbents: Adsorption behaviors and inner removal mechanism. *J Colloid Interface Sci* 673, 216–227. **DOI:** 10.1016/j.jcis.2024.06.036
- [4] Sheth Y, Dharaskar S, Khalid M, Sonawane S; (2021) An environment friendly approach for heavy metal removal from industrial wastewater using chitosan based biosorbent: a review. *Sustain Energy Technol Assess* 43, 100951. **DOI:** 10.1016/j.seta.2020.100951
- [5] Balakrishnan S, Appunni S, Chinthala M, Jacob MM, Vo DVN, Reddy SS, Kunnel ES; (2023) Chitosan-based beads as sustainable adsorbents for wastewater remediation: a review. *Environ Chem Lett* 21, 1881–1905. **DOI:** 10.1007/s10311-023-01563-9
- [6] Sharifi MJ, Nouralishahi A, Hallajani A, Askari M; (2021) Magnetic chitosan nanocomposites as adsorbents in industrial wastewater treatment: a brief review. *Cellul Chem Technol* 55(1–2), 185–205. **DOI:** 10.35812/CelluloseChemTechnol.2021.55.20

- [7] Kaczorowska MA, Bożejewicz D; (2024) The application of chitosan-based adsorbents for the removal of hazardous pollutants from aqueous solution – a review. *Sustainability* 16, 2615. **DOI:** 10.3390/su16072615
- [8] Vakili M, Deng S, Cagnetta G, Wang W, Meng P, Liu D, Yu G; (2019) Regeneration of chitosan-based adsorbents used in heavy metal adsorption: A review. *Sep Purif Technol* 224, 373–387. **DOI:** 10.1016/j.seppur.2019.05.040
- [9] Abdulrasool MM, Ruaa KM, Mays AD, Alsailawi HA, Mudhafar M, Bashi AM; (2021) Regeneration of chitosan-based adsorbent used in heavy metal adsorption. *J Life Sci* 15, 11–19. **DOI:** 10.17265/1934-7391/2021.01.002
- [10] da Silva Alves DC, Healy B, de Almeida Pinto LA, Sant’Anna Cadaval TR Jr, Breslin CB; (2021) Recent developments in chitosan-based adsorbents for the removal of pollutants from aqueous environments. *Molecules* 26(3), 594. **DOI:** 10.3390/molecules26030594
- [11] Liu X, Zhao X, Liu Y, Zhang T; (2022) Review on preparation and adsorption properties of chitosan and chitosan composites. *Polym Bull* 79, 2633–2665. **DOI:** 10.1007/s00289-021-03626-9
- [12] Eltaweil AS, Omer AM, El-Aqapa HG, Gaber NM, Attia NF, El-Subruiti GM, Mohy-Eldin MS, El-Monaem EMA; (2021) Chitosan based adsorbent for the removal of phosphate and nitrate: a critical review. *Carbohydr Polym* 274, 118671. **DOI:** 10.1016/j.carbpol.2021.118671
- [13] Kumar IA, Naushad M, Ahamad T, Viswanathan N; (2021) Development of triaminotriazine functionalized graphene oxide capped chitosan porous composite beads for nutrients remediation towards water purification. *Int J Biol Macromol* 170, 13–23. **DOI:** 10.1016/j.ijbiomac.2020.12.016
- [14] Wardhono EY, Pinem MP, Kustiningsih I, Effendy M, Clausse D, Saleh K, Guénin E; (2021) Heterogeneous deacetylation reaction of chitin under low-frequency ultrasonic irradiation. *Carbohydr Polym* 267, 118180. **DOI:** 10.1016/j.carbpol.2021.118180
- [15] Dinculescu DD, Apetroaei MR, Gîjjiu CL, Anton M, Enache L, Schröder V, Isopescu R, Rău I; (2024) Simultaneous optimization of deacetylation degree and molar mass of chitosan from shrimp waste. *Polymers* 16, 170. **DOI:** 10.3390/polym16020170
- [16] Keshvaridoostchokami M, Majidi M, Zamani A, Liu B; (2021) A review on the use of chitosan and chitosan derivatives as the bio-adsorbents for the water treatment: removal of nitrogen-containing pollutants. *Carbohydr Polym* 273, 118625. **DOI:** 10.1016/j.carbpol.2021.118625
- [17] Carrera C, Bengoechea C, Carrillo F, Calero N; (2023) Effect of deacetylation degree and molecular weight on surface properties of chitosan obtained from biowastes. *Food Hydrocoll* 137, 108383. **DOI:** 10.1016/j.foodhyd.2022.108383
- [18] Upadhyay U, Sreedhar I, Singh SA, Patel CM, Anitha KL; (2021) Recent advances in heavy metal removal by chitosan based adsorbents. *Carbohydr Polym* 251, 117000. **DOI:** 10.1016/j.carbpol.2020.117000
- [19] Wang J, Zhuang S; (2017) Removal of various pollutants from water and wastewater by modified chitosan adsorbents. *Crit Rev Environ Sci Technol* 47(23), 2331–2386. **DOI:** 10.1080/10643389.2017.1421845
- [20] Qin C, Li H, Xiao Q, Liu Y, Zhu J, Du Y; (2006) Water-solubility of chitosan and its antimicrobial activity. *Carbohydr Polym* 63(3), 367–374. **DOI:** 10.1016/j.carbpol.2005.09.023
- [21] Munim SA, Saddique MT, Raza ZA, Majeed MI; (2020) Fabrication of cellulose-mediated chitosan adsorbent beads and their surface chemical characterization. *Polym Bull* 77, 183–196. **DOI:** 10.1007/s00289-019-02711-4

- [22] Mokhtari A, Sabzi M, Azimi H; (2021) 3D porous bioadsorbents based in chitosan/alginate/cellulose nanofibers as efficient and recyclable adsorbents of anionic dye. *Carbohydr Polym* 265, 118075. **DOI:** 10.1016/j.carbpol.2021.118075
- [23] Tang H, Liu Y, Li B, Zhu L, Tang Y; (2020) Preparation of chitosan graft polyacrylic acid/graphite oxide composite and the study of its adsorption properties of cationic dyes. *Polym Sci A* 62(3), 272–283. **DOI:** 10.1134/S0965545X20030141
- [24] Vatanpour V, Salehi E, Sahebamee N, Ashrafi M; (2020) Novel chitosan/polyvinyl alcohol thin membrane adsorbents modified with detonation nanodiamonds: preparation, characterization and adsorption performance. *Arab J Chem* 13(1), 1731–1740. **DOI:** 10.1016/j.arabjc.2018.01.010
- [25] Malek NNA, Jawad AH, Ismail K, Razuan R, Alothman ZA; (2021) Fly ash modified magnetic chitosan-polyvinyl alcohol blend for reactive orange 16 dye removal: adsorption parametric optimization. *Int J Biol Macromol* 189, 464–476. **DOI:** 10.1016/j.ijbiomac.2021.08.160
- [26] Mittal H, Alili AA, Morajkar PP, Alhassan SM; (2021) GO crosslinked hydrogel nanocomposites of chitosan/carboxymethyl cellulose – a versatile adsorbent for the treatment of dyes contaminated wastewater. *Int J Biol Macromol* 167, 1248–1261. **DOI:** 10.1016/j.ijbiomac.2020.11.079
- [27] Ahmed MA, Ahmed MA, Mohamed AA; (2023) Synthesis, characterization and application of chitosan/graphene oxide/copper ferrite nanocomposite for the adsorptive removal of anionic and cationic dyes from wastewater. *RSC Adv* 13, 5337. **DOI:** 10.1039/D2RA07883J
- [28] Nayl AA, Abd-Elhamid AI, Arafa WAA, Ahmed IM, El-Shanshory AA, Abu-Saied MA, Soliman HMA; (2022) Chitosan-functionalized graphene oxide (GO@CS) beads as an effective adsorbent to remove cationic dye from wastewater. *Polymers* 14(19), 4236. **DOI:** 10.3390/polym14194236
- [29] Song X, Zhou J, Fan J, Zhang Q, Wang S; (2022) Preparation and adsorption properties of magnetic graphene oxide composites for the removal of methylene blue from water. *Mater Res Express* 9, 020002. **DOI:** 10.1088/2053-1591/ac52c6
- [30] Parastar M, Sheshmani S, Shokrollahzadeh S; (2021) Cross-linked chitosan into graphene oxide-iron(III) oxide hydroxide as nano-biosorbent for Pd(II) and Cd(II) removal. *Int J Biol Macromol* 166, 229–237. **DOI:** 10.1016/j.ijbiomac.2020.10.160
- [31] Şenol ZM, Elma E, El Messaoudi N, Mehmeti V; (2023) Performance of cross-linked chitosan-zeolite composite adsorbent for removal of Pb²⁺ ions from aqueous solutions: experimental and Monte Carlo simulations. *J Mol Liq* 391, 123310. **DOI:** 10.1016/j.molliq.2023.123310
- [32] Abukhandra MR, Mostafa M, Jumah MNB, Al-Khalawi N, Alruhaimi RS, Salama YF, Allam AA; (2022) Insight into the adsorption properties of chitosan/zeolite-A hybrid structure for effective decontamination of toxic Cd(II) and As(V) ions from aqueous environments. *J Polym Environ* 30, 295–307. **DOI:** 10.1007/s10924-021-02197-0
- [33] Yang B, Gu K, Wang S, Yi Z, Zhou Y, Gao C; (2021) Chitosan nanofiltration membranes with gradient cross-linking and improved mechanical performance for the removal of divalent salts and heavy metal ions. *Desalination* 516, 115200. **DOI:** 10.1016/j.desal.2021.115200
- [34] Alsuhaibani AM, Alayyafi AA, Albedair LA, El-Desouky MG, El-Bindary AA; (2024) Efficient fabrication of composite sponge for Cr(VI) removal via citric acid cross-linking of metal-organic framework and chitosan: adsorption isotherm,

- kinetic studies, and optimization using Box-Behnken design. *Mater Today Sustain* 26, 100732. **DOI:** 10.1016/j.mtsust.2024.100732
- [35] Babakhani A, Sataj M; (2022) Synthesis, characterization, and performance evaluation of ion-imprinted crosslinked chitosan (with sodium tripolyphosphate) for cadmium biosorption. *J Environ Chem Eng* 10(2), 107147. **DOI:** 10.1016/j.jece.2022.107147
- [36] Mazouz F, Abdelkrim S, Mokhtar A, Zahraoui M, Abdelmoumène B, Fouatih SL, Hasnaoui MA, Bengueddach A, Sassi M, Djelad A; (2023) Removal of Cu(II) ions from aqueous solutions using chitosan/zeolite composites: effects of the size of the beads and the zeolitic content. *J Polym Environ* 31, 193–209. **DOI:** 10.1007/s10924-022-02622-y
- [37] Alzahrani HK, Katowah DF; (2024) Chitosan and ferrite nanoparticles modified zeolite (ZSM-5) as adsorbent for the removal of acid red dye from water. *Int J Polym Sci* 2024, 1899137. **DOI:** 10.1155/2024/1899137
- [38] Şanlı GT, Demirhan E; (2025) Preparation and characterization of chitosan/zeolite composites for Reactive Orange 122 dye removal from aqueous media: isotherm and kinetic studies. *Biomass Convers Biorefin* 15, 3653–3662. **DOI:** 10.1007/s13399-024-05284-z
- [39] Li B, Ren Z; (2020) Superior adsorption of direct dye from aqueous solution by Y(III)-chitosan doper fly ash composite as low-cost adsorbent. *J Polym Environ* 28, 1811–1821. **DOI:** 10.1007/s10924-020-01728-5
- [40] Jawad AH, Abd Malek NN, Abdulhameed AS, Razuan R; (2020) Synthesis of magnetic chitosan-fly as/Fe₃O₄ composite for adsorption of reactive orange 16 dye: optimization by box-behnken design. *J Polym Environ* 28, 1068–1082. **DOI:** 10.1007/s10924-020-01669-z
- [41] Li B, Lin X, Zhao Y; (2024) Facile preparation and application of magnetic chitosan/fly ash composite as a hybrid biosorbent for the effective removal of direct dyes. *J Mol Liq* 397, 124148. **DOI:** 10.1016/j.molliq.2024.124148
- [42] Tran VQ, Nguyen TN, Nguyen TH, Tran VS; (2024) Adsorption of arsenate from water by iron-chitosan modified fly ash. *IOP Conf Ser Earth Environ Sci* 1383(1), 012010. **DOI:** 10.1088/1755-1315/1383/1/012010
- [43] Begum S, Yuhana NY, Saled NM, Kamarudin NHN, Sulong AB; (2021) Review of chitosan composite as a heavy metal adsorbent: material preparation and properties. *Carbohydr Polym* 259, 117613. **DOI:** 10.1016/j.carbpol.2021.117613
- [44] El Knidri H, Belaabed R, Addaou A, Laajeb A, Lahsini A; (2018) Extraction, chemical modification and characterization of chitin and chitosan. *Int J Biol Macromol* 120, 1181–1189. **DOI:** 10.1016/j.ijbiomac.2018.08.139
- [45] Yang X, Lan W, Sun X; (2023) Antibacterial and antioxidant properties of phenolic acid grafted chitosan and its application in food preservation: a review. *Food Chem* 428, 136788. **DOI:** 10.1016/j.foodchem.2023.136788
- [46] Vafakish B, Wilson LD; (2020) Cu(II) ions adsorption by aniline grafted chitosan and its responsive fluorescence properties. *Molecules* 25(5), 1052. **DOI:** 10.3390/molecules25051052
- [47] Yusof NH, Foo KY, Wilson LD, Hameed BH, Hussin MH, Sabar S; (2020) Microwave-assisted synthesis of polyethyleneimine grafted chitosan beads for the adsorption of acid red 27. *J Polym Environ* 28, 542–552. **DOI:** 10.1007/s10924-019-01628-3
- [48] Feng L, Li X, Lu W, Liu Z, Xu C, Chen Y, Zheng H; (2020) Preparation of a graft modified flocculant based on chitosan by ultrasonic initiation and its synergistic effect with kaolin for the improvement of acid blue 83 (AB 83) removal. *Int J Biol Macromol* 150, 617–630. **DOI:** 10.1016/j.ijbiomac.2020.02.076

- [49] Huang KX, Zhou LY, Chen JQ, Peng N, Chen HX, Gu HZ, Zou T; (2023) Applications and perspectives of quaternized cellulose, chitin and chitosan: a review. *Int J Biol Macromol* 242, 124990. **DOI:** 10.1016/j.ijbiomac.2023.124990
- [50] Andreica BI, Cheng X, Marin L; (2020) Quaternary ammonium salts of chitosan. A critical overview on the synthesis and properties generated by quaternization. *Eur Polym J* 139, 110016. **DOI:** 10.1016/j.eurpolymj.2020.110016
- [51] Ye Y, Zhang T, Lv L, Chen Y, Tang W, Tang S; (2021) Functionalization of chitosan by grafting sulfhydryl groups to intensify the adsorption of arsenite from water. *Colloids Surf A Physicochem Eng Asp* 622, 126601. **DOI:** 10.1016/j.colsurfa.2021.126601
- [52] Huang LY, Li W, Du N, Lu HQ, Meng LD, Huang KY, Li K; (2022) Preparation of quaternary ammonium magnetic chitosan microspheres and their application for Congo red adsorption. *Carbohydr Polym* 297, 119995. **DOI:** 10.1016/j.carbpol.2022.119995
- [53] Zhang R, Meng B, Wang X, Liu Y, Zeng J, Weng G, Xu J, Xiang J, Song Y, Jin L; (2025) Quaternized Fe₃O₄@chitosan nanoparticles for efficient and selective isolation of heparin. *Int J Biol Macromol* 293, 139368. **DOI:** 10.1016/j.ijbiomac.2024.139368
- [54] Guo LY, Lu HQ, Rackemann D, Shi C, Li W, Li K, Doherty WOS; (2021) Quaternary ammonium-functionalized magnetic chitosan microspheres as an effective green adsorbent to remove high-molecular-weight invert sugar alkaline degradation products (HISADPs). *Chem Eng J* 416, 129084. **DOI:** 10.1016/j.cej.2021.129084
- [55] Zhang S, Ding J, Tian D, Kang R, Zhao X, Chang M, Yang W, Xie H, Lu M; (2023) As(V) removal from aqueous environments using quaternary ammonium modified ZIF-8/chitosan composite adsorbent. *Appl Surf Sci* 614, 156179. **DOI:** 10.1016/j.apsusc.2022.156179
- [56] Xu X, Ouyang Xk, Yang LX; (2021) Adsorption of Pb(II) from aqueous solutions using crosslinked carboxylated chitosan/carboxylated nanocellulose hydrogel beads. *J Mol Liq* 322, 114523. **DOI:** 10.1016/j.molliq.2020.114523
- [57] Surgutskaja N, Martino AD, Zednik J, Ozaltin K, Lovecká L, Bergerová ED, Kimmer D, Svoboda J, Sedlarik V; (2020) Efficient Cu²⁺, Pb²⁺ and Ni²⁺ ion removal from wastewater using electrospun DTPA-modified chitosan/polyethylene oxide nanofibers. *Sep Purif Technol* 247, 116914. **DOI:** 10.1016/j.seppur.2020.116914
- [58] Hu D, Lian Z, Xian H, Jiang R, Wang N, Weng Y, Peng X, Wang S, Ouyang XK; (2020) Adsorption of Pb(II) from aqueous solution by polyacrylic acid grafted magnetic chitosan nanocomposite. *Int J Biol Macromol* 154, 1537–1547. **DOI:** 10.1016/j.ijbiomac.2019.11.038
- [59] El-Soad AM, Lazzara G, El-Magied MO, Cavallaro G, Al-Otaibi J, Sayyed MI, Kovaleva EG; (2022) Chitosan functionalized with carboxyl groups as a recyclable biomaterial for the adsorption of Cu(II) and Zn(II) ions in aqueous media. *Int J Mol Sci* 23(4), 2396. **DOI:** 10.3390/ijms23042396
- [60] Anush SM, Chandan HR, Gayathri BH, Asma, Manju N, Vishalakshi B, Kalluraya B; (2020) Graphene oxide functionalized chitosan-magnetite nanocomposite for removal of Cu(II) and Cr(VI) from waste water. *Int J Biol Macromol* 164, 4291–4402. **DOI:** 10.1016/j.ijbiomac.2020.09.059
- [61] Yuan D, Zhang W, Cui J, He L, Wang J, Yan C, Kou Y, Li J; (2020) Facile fabrication of magnetic phosphorylated chitosan for removal of Co(II) in water treatment: separation properties and adsorption mechanisms. *Environ Sci Pollut Res* 27, 2588–2598. **DOI:** 10.1007/s11356-019-07026-5

- [62] Gan H, Zhang L, Wang Q, Xin Q, Xiong Y, Hu E, Lei Z, Wang H, Wang H; (2023) Phosphorylation improved the competitive U/V adsorption of chitosan-based adsorbent containing amidoxime for rapid uranium extraction from seawater. *Int J Biol Macromol* 238, 124074. **DOI:** 10.1016/j.ijbiomac.2023.124074
- [63] Subramaniam S, Foo KY, Yusof ENMd, Jawad AH, Wilson LD, Sabar S; (2021) Hydrothermal synthesis of phosphorylated chitosan and its adsorption performance towards Acid Red 88 dye. *Int J Biol Macromol Part B* 193, 1716–1726. **DOI:** 10.1016/j.ijbiomac.2021.11.009
- [64] Palacio DA, Vásquez V, Rivas BL; (2020) N-Alkylated chitosan coupled to the liquid-phase polymer based retention (LPR) technique to remove arsenic(V) from aqueous systems. *J Hazard Mater* 400, 123216. **DOI:** 10.1016/j.jhazmat.2020.123216
- [65] Sharfan IB, Aldhawi ZA, Abdulhamid MA; (2024) Rapid eco-friendly selective dye removal using modified chitosan-based sponges: synthesis, characterization and application. *Int J Biol Macromol* 275(1), 133577. **DOI:** 10.1016/j.ijbiomac.2024.133577
- [66] Palacio DA, Muñoz C, Meléndrez M, Rabanal-León WA, Murillo-López JA, Palencia M, Rivas BL; (2023) Comparative study of the removal efficiency of nalidixic acid by poly[(4-vinylbenzyl)trimethylammonium chloride] and N-alkylated chitosan through the ultrafiltration technique and its approximation through theoretical calculations. *Polymers* 15(15), 3185. **DOI:** 10.3390/polym15153185
- [67] Esquivel S, Zuñiga M, Meléndrez M, Pereira E, Urbano BF, Rivas BL, Palacio DA; (2025) Removal of ciprofloxacin using polymeric nanocomposites synthesized from alkylated chitosan ionic macromonomers, ionic monomers and hydrotalcite. *Int J Biol Macromol* 300, 140303. **DOI:** 10.1016/j.ijbiomac.2025.140303
- [68] Naidoo S, Nomadolo N, Matshe WMR, Cele Z, Balogun M; (2019) Exploring the potential of N-acylated chitosan for the removal of toxic pollutants from wastewater. *IOP Conf Ser Mater Sci Eng* 655, 012047. **DOI:** 10.1088/1757-899X/655/1/012047
- [69] Mahmoud RK, Mohamed F, Gaber E, Abdel-Gawad OF; (2022) Insights into the synergistic removal of copper(II), cadmium(II), and chromium(III) ions using modified chitosan based on Schiff Bases-g-poly(acrylonitrile). *ACS Omega* 7, 42012–42026. **DOI:** 10.1021/acsomega.2c03809
- [70] Tian H, Yang P, Li G, Ma F, Li J, Li Y, Cui W, Zhang Z; (2024) Preparation of ultra-light, highly compressible, and biodegradable chitosan porous materials for heavy metal adsorption, dye adsorption and oil-water separation. *Carbohydr Polym* 346, 122662. **DOI:** 10.1016/j.carbpol.2024.122662
- [71] Agha HM, Abdulhameed AS, Jawad AH, Khadiran T, Alothman ZA, Wilson LD; (2025) Facile synthesis of cross-linked chitosan -genipin/algae composite adsorbent for cationic methyl violet dye removal: robust modeling of adsorption using the box-behnken design. *J Inorg Organomet Polym Mater* 35, 1084–1099. **DOI:** 10.1007/s10904-024-03327-6
- [72] Chen Q, Qi Y, Jiang Y, Quan W, Luo H, Wu K, Li S, Ouyang Q; (2022) Progress in research of chitosan chemical modification technologies and their applications. *Mar Drugs* 20(8), 536. **DOI:** 10.3390/md20080536
- [73] Benettayeb A, Ghosh S, Usman M, Seihoub FZ, Sohoo I, Chia CH, Sillanpää; (2022) Some well-know alginate and chitosan modifications used in adsorption: a review. *Water* 14(9), 1353. **DOI:** 10.3390/w14091353

- [74] Wang W, Meng Q, Li Q, Liu J, Zhou M, Jin Z, Zhao K; (2020) Chitosan derivatives and their application in biomedicine. *Int J Mol Sci* 21, 487. **DOI:** 10.3390/ijms21020487
- [75] Baskar AV, Bolan N, Hoang SA, Sooriyakumar P, Kumar M, Singh L, Jasemizad T, Padhye LP, Singh G, Vinu A, Sarkar B, Kirkham MB, Rinklebe J, Wang S, Wang H, Balasubramanian R, Siddique KH; (2022) Recovery, regeneration and sustainable management of spent adsorbents from wastewater treatment streams: a review. *Sci Total Environ* 822, 153555. **DOI:** 10.1016/j.scitotenv.2022.153555
- [76] Francis AO, Zaini MAA, Muhammad IM, Abdulsalam S, El-Nafaty UA; (2023) Physicochemical modification of chitosan adsorbent: a perspective. *Biomass Convers Biorefin* 13, 5557–5575. **DOI:** 10.1007/s13399-021-01599-3
- [77] Zeng H, Sun S, Yu Y, Zhang J, Li D; (2021) Column studies on the adsorption of As(V) by granular chitosan adsorbent prepared with backwashing iron-containing sludge. *Colloids Surf A Physicochem Eng Asp* 627, 127247. **DOI:** 10.1016/j.colsurfa.2021.127247
- [78] Akili M, Deng S, Shen L, Shan D, Liu D, Yu G; (2019) Regeneration of chitosan-based adsorbents for eliminating dyes from aqueous solutions. *Sep Purif Rev* 48(1), 1–13. **DOI:** 10.1080/15422119.2017.1406860
- [79] Kim HR, Jang JW, Park JW; (2016) Carboxymethyl chitosan-modified magnetic-cored dendrimer as an amphoteric adsorbent. *J Hazard Mater* 317, 608–616. **DOI:** 10.1016/j.hazmat.2016.06.025
- [80] Kwok KCM, Koong LF, Al Ansari T, McKay G; (2018) Adsorption/desorption of arsenite and arsenate on chitosan and nanochitosan. *Environ Sci Pollut Res* 25, 14734–14742. **DOI:** 10.1007/s11356-018-1501-9
- [81] da Silva Bruckmann F, da Rosa Salles T, Knani S, Graba B, Baumann L, Müller EI, Garcia WJS, de Oliveira AH, do Carmo M Alves M, Morais J, da Boit Martinello K, Silva LFO, Dotto GL, Rhoden CRB; (2024) Removal of ivermectin from aqueous on chitosan-based magnetic adsorbent. *Inorg Chem Commun* 169, 113006. **DOI:** 10.1016/j.inoche.2024.113006
- [82] Mao J, Lin S, Lu XJ, Wu XJ, Zhou T, Yun YS; (2020) Ion-imprinted chitosan fiber for recovery of Pd(II): obtaining high selectivity through selective adsorption and two-step desorption. *Environ Res* 182, 108995. **DOI:** 10.1016/j.envres.2019.108995
- [83] Vijayalakshmi K, Devi BM, Latha S, Gomathi T, Sudha PN, Venkatesan J, Anil S; (2017) Batch adsorption and desorption studies on the removal of lead (II) from aqueous solution using nanochitosan/sodium alginate/microcrystalline cellulose beads. *Int J Biol Macromol* 104, 1483–1494. **DOI:** 10.1016/j.ijbiomac.2017.04.120
- [84] Maity J, Ray SK; (2018) Chitosan based nano composite adsorbent-synthesis, characterization and application for adsorption of binary mixtures of Pb(II) and Cd(II) from water. *Carbohydr Polym* 182, 159–171. **DOI:** 10.1016/j.carbpol.2017.10.086
- [85] Gao Y, Bao S, Zhang L, Zhang L; (2020) Nitrate removal by using chitosan/zeolite molecular sieves composite at low temperature: characterization, mechanism, and regeneration studies. *Desalin Water Treat* 203, 160–171. **DOI:** 10.5004/dwt.2020.26219
- [86] Liu T, Fu J, Gou D, Hu Y, Tang Q, Zhao J, Li X; (2021) Chitosan-derived magnetic nanomaterials: synthesis, characterization, and nitrite adsorption in water. *J Nanomater* 2021, 6420341. **DOI:** 10.1155/2021/6420341

- [87] Yang J, Chen X, Zhang J, Wang Y, Wen H, Xie J; (2021) Role of Chitosan-Based Hydrogels in Pollutants Adsorption and Freshwater Harvesting: A Critical Review. *Int J Biol Macromol* 189, 53–64. **DOI:** 10.1016/j.ijbiomac.2021.08.047