

Chitosan-Based Adsorption for Heavy Metal Removal in Electroplating Wastewater: A Sustainable and Cost-Effective Approach

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ABSTRACT

Electroplating wastewater contains significant concentrations of toxic heavy metals including copper (Cu), zinc (Zn), nickel (Ni), and iron (Fe), which pose severe environmental and public health risks when discharged without adequate treatment. Conventional treatment technologies such as chemical precipitation, membrane filtration, ion exchange, and electrochemical methods, while effective, are often associated with high operational costs, secondary pollution, and excessive energy consumption. Chitosan, a biopolymer derived from the deacetylation of chitin found abundantly in crustacean shells, has emerged as a promising, sustainable, and cost-effective adsorbent for heavy metal removal from aqueous solutions. This review comprehensively examines the application of chitosan-based adsorbents for the removal of Cu(II), Zn(II), Ni(II), and Fe(II/III) from electroplating wastewater. The production process of chitosan from arthropod and mollusc sources was discussed, along with detailed characterization techniques including Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS), Thermogravimetric Analysis (TGA), X-ray Fluorescence (XRF), and textural property analysis. The adsorption mechanisms, including complexation, electrostatic attraction, and ion exchange, are critically evaluated. Furthermore, the influence of environmental factors such as pH, temperature, contact time, adsorbent dosage, and initial metal concentration on chitosan adsorption performance is assessed.

Keywords: Chitosan; Heavy metal removal; Adsorption; Electroplating wastewater; Biopolymer

1.0 INTRODUCTION

Heavy metals are non-biodegradable and tend to accumulate in living organisms through food chain bioaccumulation, causing severe health effects including neurological disorders, kidney and liver damage, respiratory complications, and carcinogenic effects (Rostam *et al.*, 2026). In 2011, the National Environmental Standards and Regulations Enforcement Agency (NESREA) established strict guidelines for maximum permissible concentrations of heavy metals in industrial effluent, as presented in Table 1.

Table 1: Heavy Metal Concentration Limits in Drinking Water

Element	Limit (mg/L)
Cu	0.1
Zn	2.0
Ni	0.5
Fe	3.0

Source: NESREA(2011)

These stringent regulations necessitate the development of efficient, economically viable, and environmentally sustainable treatment technologies for

the removal of heavy metals from electroplating wastewater.

Various treatment technologies have been employed for heavy metal removal from wastewater, including chemical precipitation, coagulation-flocculation, membrane filtration, ion exchange, electrochemical methods, and adsorption (Rakkak *et al.*, 2022; Zamora-Ledezma *et al.*, 2021). Among these, adsorption has gained considerable attention due to its high efficiency, operational simplicity, design flexibility, and potential for adsorbent regeneration and reuse (Ali *et al.*, 2019).

Chitosan, a cationic polysaccharide obtained through the alkaline deacetylation of chitin, has emerged as one of the most promising biosorbents for heavy metal removal (Sheth *et al.*, 2021). Chitin is the second most abundant natural polysaccharide after cellulose, found primarily in the exoskeletons of crustaceans such as crabs, shrimp, prawns, and lobsters. The unique chemical structure of chitosan, with its high density of amino ($-NH_2$) and hydroxyl ($-OH$) functional groups, provides excellent metal-binding capabilities. This review aims to provide a systematic and comprehensive assessment of chitosan-based

adsorption for removing heavy metals from electroplating wastewater. Specifically, the review examines: (i) the major conventional and emerging technologies used for heavy metal removal and their limitations; (ii) the sources, production processes, and key physicochemical characteristics of chitosan; (iii) the characterization techniques used to evaluate the structural, morphological, thermal, elemental, and textural properties of chitosan-based adsorbents; (iv) the adsorption performance of chitosan and its derivatives for the removal of Cu(II), Zn(II), Ni(II), and Fe(II/III); (v) the adsorption mechanisms and the role of chitosan functional groups in metal binding; (vi) the influence of operational and environmental parameters, including pH, temperature, contact time, adsorbent dosage, and initial metal concentration; (vii) modification strategies for enhancing the adsorption

capacity, selectivity, and stability of chitosan; and (viii) the current challenges, scale-up considerations, and future research directions required to facilitate the practical application of chitosan-based adsorbents for sustainable electroplating wastewater treatment.

2.0 DIFFERENT TECHNIQUES USED FOR METAL REMOVAL IN WASTEWATER

The treatment of heavy metal-contaminated wastewater employs a diverse array of technologies, each with distinct advantages and limitations. These techniques can be broadly classified into chemical, physical, biological, and hybrid methods (Aziz *et al.*, 2023). Figure 1 provides an overview of the major techniques used for the removal of heavy metals from aqueous solutions.

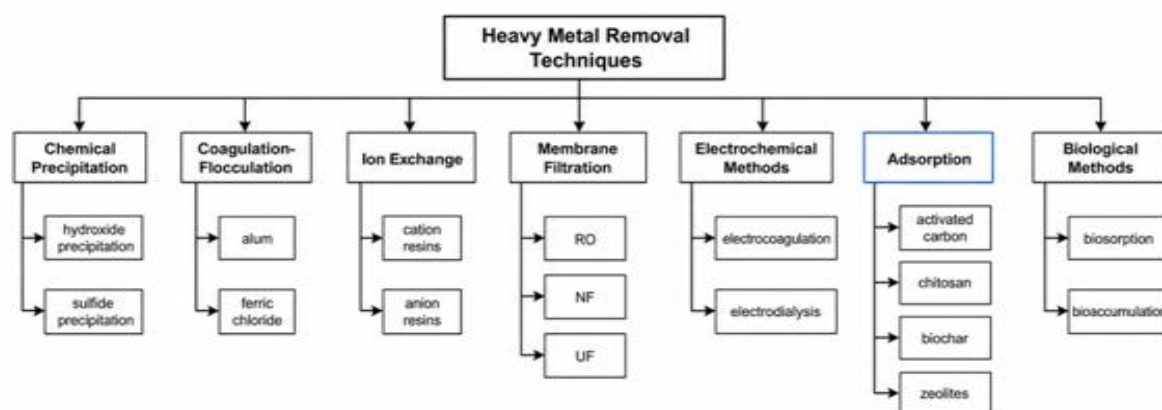


Figure 1. Techniques used for the removal of heavy metals from aqueous solutions.

Figure 1 illustrates the major categories of heavy metal removal techniques, which include chemical precipitation, coagulation-flocculation, ion exchange, membrane filtration, electrochemical methods, adsorption, and biological methods.

2.1 Chemical Precipitation

Chemical precipitation is one of the most widely employed methods for heavy metal removal from industrial wastewater. This technique involves the addition of chemical reagents such as calcium hydroxide (lime), sodium hydroxide, or sodium sulfide to convert dissolved metal ions into insoluble metal hydroxides or sulfides, which can then be separated from the aqueous phase by sedimentation or filtration (Pohl, 2020). Hydroxide precipitation operates optimally at pH values between 8 and 11, where most heavy metals form insoluble hydroxide precipitates.

2.2 Coagulation-Flocculation

Coagulation-flocculation involves the addition of coagulants such as aluminum sulfate, ferric chloride, or polyaluminum chloride to destabilize colloidal particles containing heavy metals, followed by the addition of flocculants to aggregate the destabilized

particles into larger flocs that can be separated by sedimentation (Iwuozor, 2019).

2.3 Ion Exchange

Ion exchange employs synthetic resins containing functional groups that can exchange cations or anions with heavy metal ions in solution. Cation exchange resins containing sulfonic, carboxylic, or phosphonic groups are commonly used for heavy metal removal (Qasem *et al.*, 2021). The method offers high removal efficiency and selectivity, and the resins can be regenerated for reuse.

2.4 Membrane Filtration

Membrane filtration technologies include reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF), which separate heavy metal ions from wastewater using semi-permeable membranes of varying pore sizes (Castro *et al.*, 2024). These methods offer high removal efficiency and can produce high-quality permeate, but are associated with high capital and operational costs, membrane fouling, and concentrate disposal challenges.

2.5 Electrochemical Methods

Electrochemical treatment methods, including electrocoagulation, electroflotation, and electrodialysis, utilize electrical current to remove heavy metals from wastewater. These methods offer precise control and multi-metal removal capability without chemical additives (Rivera-Parra *et al.*, 2022; Gök and Gulyasar, 2025).

2.6 Adsorption

Adsorption is a surface phenomenon in which heavy metal ions are transferred from the aqueous phase to the surface of a solid adsorbent through physical or chemical interactions. Common adsorbents include activated carbon, zeolites, biochar, metal oxides, clay minerals, and biopolymer-based materials such as chitosan (Ali *et al.*, 2019; Paranjape *et al.*, 2022; Sahoo and Prelot, 2020). Adsorption offers several advantages, including high efficiency at low metal concentrations, operational simplicity, design flexibility, and the potential for adsorbent regeneration (Syeda *et al.*, 2022).

2.7 Biological Methods

Biological methods encompass biosorption, bioaccumulation, and biomineralization processes that utilize living organisms or their biomass to sequester heavy metals. Bacteria, algae, fungi, and plant biomass have been investigated as biosorbents for heavy metal removal (Nnaji *et al.*, 2023). While these methods are environmentally friendly and cost-effective, they are typically slow and have limited capacity compared to physicochemical methods.

3.0 EFFECTIVENESS OF CHITOSAN IN METAL REMOVAL FROM WASTEWATER

Chitosan has demonstrated remarkable effectiveness as an adsorbent for heavy metal removal from wastewater, owing to its unique chemical structure and physicochemical properties. The effectiveness of chitosan in metal removal can be attributed to several factors, including its high density of amino and hydroxyl functional groups, its cationic nature in acidic solutions, and its versatile modification potential (Zhang *et al.*, 2021; Min *et al.*, 2026).

3.1 Comparison of Technologies for Heavy Metal Removal

A comparison of various heavy metal removal technologies reveals that chitosan-based adsorption offers a unique combination of advantages including high efficiency (46–99% for Cu, Zn, Ni, Fe), wide pH range, renewable and biodegradable nature, and low cost due to abundant raw material availability from seafood processing waste. In contrast, chemical precipitation generates large volumes of sludge, membrane filtration involves high costs and fouling issues, and electrochemical methods require high energy consumption (Rahman *et al.*, 2022).

3.2 Chitosan Production Process

The production of chitosan from crustacean shells involves a well-established multi-step chemical process that transforms shell waste into a valuable biopolymer. Figure 2 illustrates the chitosan production process from raw crustacean shell materials.

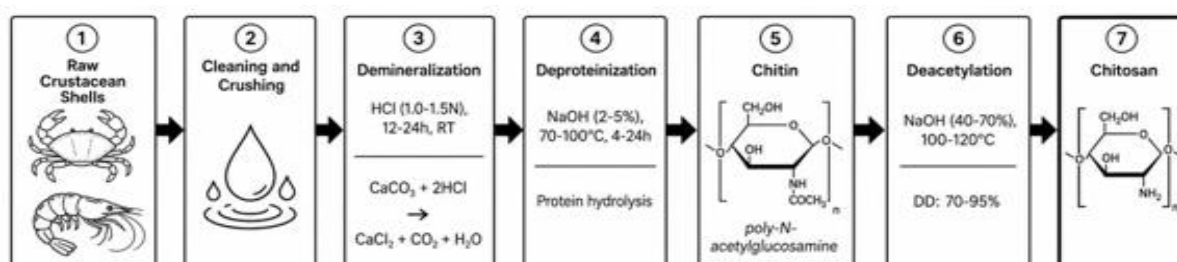


Figure 2. Chitosan production process showing sequential steps from raw shell waste to purified chitosan.

Figure 2 depicts the sequential steps involved in chitosan production from crustacean shell waste. The process begins with the collection and cleaning of shell waste from seafood processing industries. The shells, which typically contain 30 to 40% protein, 30 to 50% minerals (primarily calcium carbonate), and 20 to 30% chitin by dry weight, undergo three principal chemical treatments (Pellis *et al.*, 2022).

The first step, demineralization, involves treating the crushed shells with dilute hydrochloric acid (typically 1.0 to 1.5 N HCl) at a solid-to-liquid ratio of 1:10 to

1:15 for 12 to 24 hours at room temperature (Frenchibai *et al.*, 2025). The acid reacts with calcium carbonate to produce soluble calcium chloride and carbon dioxide gas, effectively removing the mineral content.

The second step, deproteinization, involves treating the demineralized shells with sodium hydroxide solution (typically 2 to 5% NaOH) at elevated temperatures (70 to 100°C) for 4 to 24 hours to remove the protein content (Koirala *et al.*, 2024). The alkaline treatment hydrolyzes the protein component, which is then washed away, leaving behind crude chitin.

The third step, deacetylation, is the critical process that converts chitin into chitosan. This involves treating the chitin with concentrated sodium hydroxide solution (40 to 70% NaOH) at elevated temperatures (100 to 120 °C) for several hours (Ewais *et al.*, 2023). During deacetylation, the N-acetyl groups on the chitin backbone are removed, exposing free amino groups that impart the unique adsorption properties of chitosan. The degree of deacetylation (DD), which represents the proportion of deacetylated units, typically ranges from 70 to 95% and directly influences the adsorption capacity of the resulting chitosan (Mathaba *et al.*, 2023).

3.3 Characterization of Chitosan

The characterization of chitosan and chitosan-based adsorbents is essential for understanding their

structural properties, functional group composition, crystallinity, thermal stability, and morphology, all of which influence their adsorption performance.

3.3.1 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy is the most widely used technique for characterizing chitosan and its derivatives. The FTIR spectrum of chitosan displays several characteristic absorption bands that provide information about its functional group composition (Promkatkaew *et al.*, 2023; Abdel-Raouf *et al.*, 2024). The broad absorption band observed between 3200 and 3600 cm^{-1} corresponds to the overlapping stretching vibrations of O–H and N–H groups, a signature feature of chitosan. Figure 3 presents the FTIR spectrum of chitosan with characteristic peaks annotated.

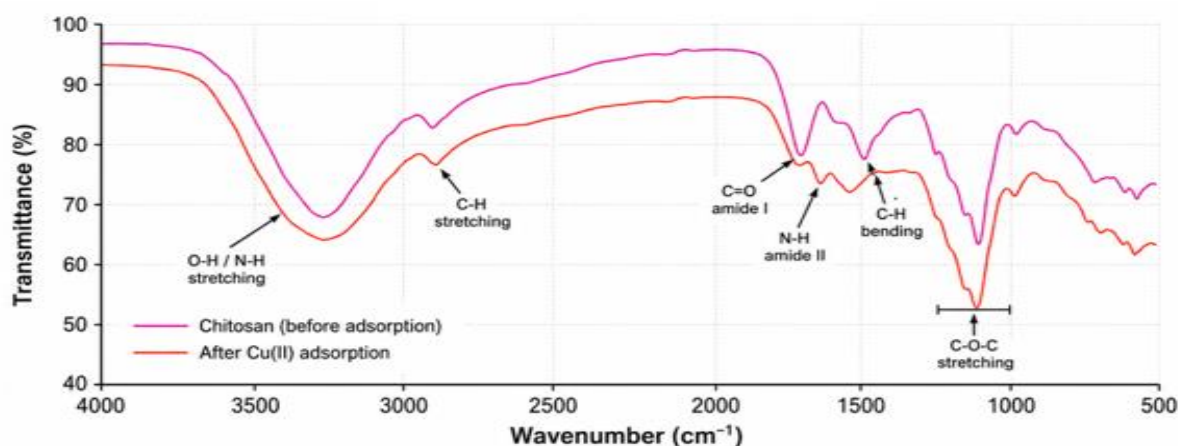


Figure 3. FTIR spectrum of chitosan showing characteristic absorption bands: O–H/N–H stretching (3200–3600 cm^{-1}), C=O amide I (1635–1660 cm^{-1}), and N–H amide II (1560–1590 cm^{-1}). Red/orange overlay shows spectrum after Cu(II) adsorption.

The absorption bands at approximately 1635–1660 cm^{-1} and 1560–1590 cm^{-1} were assigned to the C=O stretching vibration (amide I band) and the N–H bending vibration (amide II band), respectively. These bands are indicative of the residual N-acetyl groups remaining in the chitosan structure. Changes in the position and intensity of these bands after metal adsorption provide evidence for the involvement of amino and hydroxyl groups in the metal-binding mechanism (Nasir *et al.*, 2018).

3.3.2 X-ray Diffraction (XRD)

XRD analysis provides information about the crystalline structure and degree of crystallinity of chitosan. The XRD pattern of chitosan typically exhibits two characteristic peaks: a smaller peak at approximately $2\theta = 10^\circ$ corresponding to the (020) hydrated crystalline plane, and a more intense peak at approximately $2\theta = 20^\circ$ corresponding to the (110) anhydrous crystalline plane (Koirala *et al.*, 2024; Ravi *et al.*, 2025). Figure 4 presents the XRD pattern of chitosan.

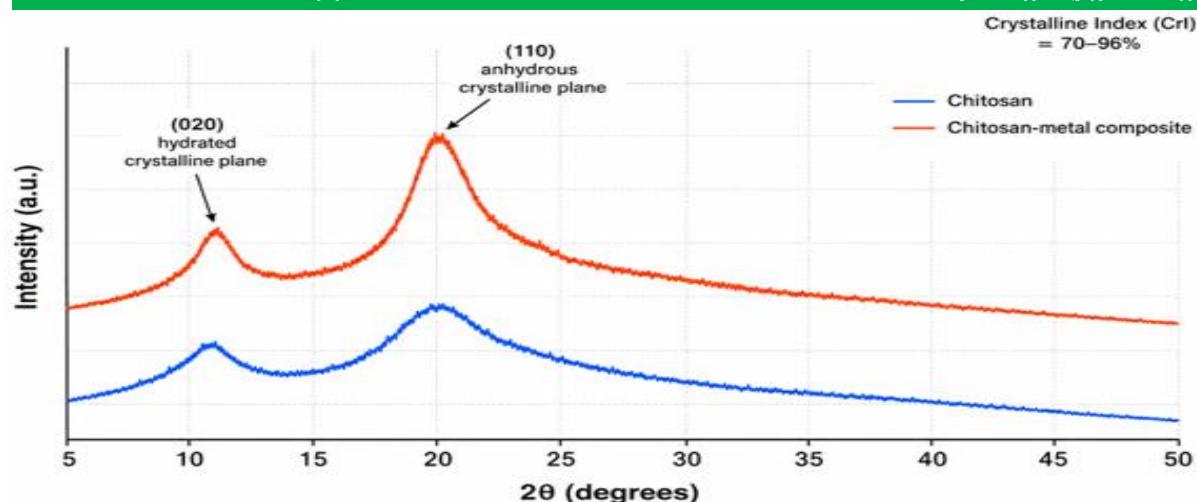


Figure 4. XRD pattern of chitosan showing semi-crystalline peaks at $2\theta = 10^\circ$ (020 hydrated crystalline plane) and $2\theta = 20^\circ$ (110 anhydrous crystalline plane). Red/orange overlay shows chitosan-metal composite pattern.

The crystalline index (CrI) of chitosan, calculated from the XRD data, provides a figure/micrograph measure of its crystallinity. CrI values vary depending on the source and processing conditions, with reported values ranging from 70 to 96% for chitosan derived from different crustacean sources (Tran *et al.*, 2017). The crystallinity of chitosan influences its adsorption properties, as amorphous regions are more accessible to metal ions and provide greater swelling capacity, while crystalline regions provide mechanical stability.

3.3.3 Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS)

SEM-EDS analysis provides morphological and elemental composition information about chitosan-based adsorbents. SEM images of chitosan typically reveal a rough, porous surface with fibrous nanostructures that provide a high surface area for adsorption (Al-Mur *et al.*, 2026). EDS analysis confirms the elemental composition of chitosan and its composites, typically showing the presence of carbon (C), oxygen (O), and nitrogen (N) as the primary elements. After metal adsorption, EDS analysis reveals the presence of metal peaks on the adsorbent surface, providing direct evidence for successful metal uptake (Nasir *et al.*, 2018).

3.3.4 Thermogravimetric Analysis (TGA)

TGA provides information about the thermal stability and decomposition behavior of chitosan and its derivatives. The TGA curve of pure chitosan typically exhibits two or three distinct stages of weight loss (Dambuza *et al.*, 2025). The first stage, occurring between 30 and 150°C, corresponds to the loss of adsorbed and bound water molecules, with a weight loss of approximately 8 to 16%. The second stage, occurring between 200 and 400°C, represents the primary thermal degradation of the chitosan polymer, involving dehydration of saccharide rings, depolymerization, and decomposition of the acetylated and deacetylated units, with a weight loss of approximately 30 to 50% (Sultan *et al.*, 2023). The thermal stability of chitosan-based composites is generally enhanced compared to pristine chitosan, as evidenced by higher onset decomposition temperatures and increased char residue (Dambuza *et al.*, 2025; Monir *et al.*, 2024).

3.3.5 X-ray Fluorescence (XRF)

XRF spectroscopy is used for elemental analysis of chitosan-based adsorbents and provides quantitative information about the metal content before and after adsorption. XRF analysis can confirm the presence of adsorbed heavy metals and quantify the adsorption capacity. Table 3.1 depicts typical chemical concentration range for the chitosan sample.

Table 2: Chemical element concentration of chitosan

Element/oxide	Conc. Range (%) (Eddya <i>et al.</i> , 2020)	Interpretation
CaO	0.21-0.5	Indicates effective demineralization
SiO ₂	0.18-0.97	May originate from environmental contamination
Na ₂ O	Trace-0.58	Possible residual alkali from NaOH treatment
MgO	Trace-1.34	Residual natural mineral component
P ₂ O ₃	0.33-4.44	Residual phosphate/mineral component

Fe ₂ O ₃	Trace	Natural trace element
K ₂ O	Trace-0.09	Residual mineral content
Cl	Trace-0.40	Possible residual chloride after acid treatment
Others	Trace	Minor impurities depending on source

3.4 Adsorption of Copper, Zinc, Nickel, and Iron

3.4.1 Copper Adsorption

Copper is one of the most extensively studied heavy metals in chitosan adsorption research. Several modified chitosan systems exceed 130 mg/g at pH around 5–6, including EDTA-crosslinked CSECM at 142.95 mg/g at pH 5.5, melamine-modified magnetic chitosan at 2.58 mmol/g at pH 5.5, and other functionalized materials from about 140.9 to 215.5 mg/g (Manzoor *et al.*, 2019). Modified chitosan adsorbents have shown significantly enhanced capacities, including chitosan/PVA composite with a capacity of 303.29 mg/g (Sopanrao *et al.*, 2023), EDTA-grafted chitin with 223.70 mg/g (Azizinezhad, 2024), and magnetic chitosan/graphene oxide nanocomposite with 217.4 mg/g (Wang *et al.*, 2023). The removal efficiency of chitosan for Cu(II) from industrial electroplating wastewater was reported to be 79.09% using PVA-modified chitosan composite (Sopanrao *et al.*, 2023).

3.4.2 Zinc Adsorption

Zinc removal from aqueous solutions using chitosan has been investigated using various forms and modifications. chitosan-biochar composite achieved a maximum adsorption capacity of 117.50 mg/g for Zn(II) (Sopanrao *et al.*, 2025). PVA-modified chitosan composite showed a removal efficiency of 75% for Zn(II) from electroplating wastewater (Sopanrao *et al.*, 2023). MnFe₂O₄/chitosan/Schiff base nanocomposite demonstrated effective Zn²⁺ removal from aqueous solution (Alhalili and Abdelrahman, 2024).

3.4.3 Nickel Adsorption

Nickel adsorption by chitosan-based adsorbents has been widely studied. Amino-functionalized chitosan achieved a maximum adsorption capacity of 150 mg/g for Ni(II) (Igberase and Mkhize, 2025). The optimal pH for Ni(II) adsorption is typically between 5 and 7, where the amino groups are deprotonated and available for coordination. Chitosan coated PVC beads demonstrated effective adsorptive removal of nickel ions from water (Cahyo *et al.*, 2025).

3.4.4 Iron Adsorption

Iron removal using chitosan-based adsorbents has shown promising results. Li *et al.* (2023) reported on harnessing low-cost adsorbents for removal of heavy metals including iron in contaminated water. PVA-modified chitosan composite and carboxymethyl chitosan showed adsorption capacities for Fe(II) of 135.14 mg/g and 147.06 mg/g, respectively (Sopanrao *et al.*, 2023).

3.5 Chemical Structure and Functional Groups of Chitosan

The chemical structure of chitosan is fundamental to understanding its adsorption properties. Chitosan is a linear polysaccharide composed of randomly distributed β -(1 $\rightarrow$ 4)-linked D-glucosamine (deacetylated unit) and N-acetyl-D-glucosamine (acetylated unit). The presence of amino (–NH₂) and hydroxyl (–OH) groups on the polymer backbone serves as the primary binding sites for heavy metal ions. Figure 5 illustrates the chemical structure of chitosan with its key functional groups.

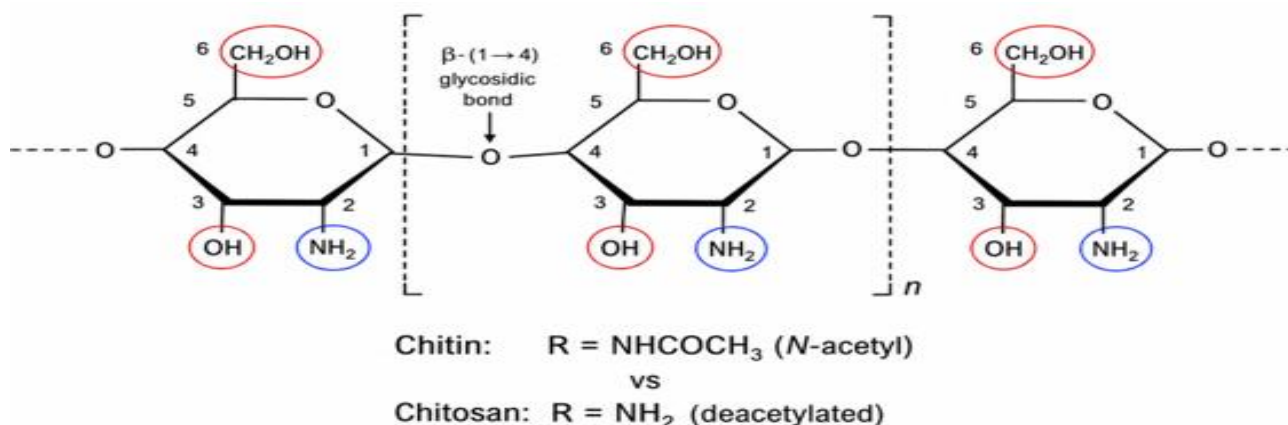


Figure 5. Chemical structure of chitosan showing the β -(1 $\rightarrow$ 4)-linked D-glucosamine polymer backbone with amino (–NH₂) and hydroxyl (–OH) functional groups. Comparison with chitin structure showing N-acetyl groups.

The amino groups at the C2 position are the most important functional groups for heavy metal

adsorption. In acidic solutions (pH < 6.5), the amino groups become protonated (–NH₃⁺), making them available for electrostatic interactions with anionic

species. In near-neutral solutions, the deprotonated amino groups ($-\text{NH}_2$) provide lone pair electrons for coordination with metal cations. The hydroxyl groups at C3 and C6 positions also contribute to metal binding through chelation and hydrogen bonding mechanisms (De Sousa Victor, 2020; Shariatina *et al.*, 2019).

3.6 Adsorption Mechanisms for Heavy Metal Removal

The mechanism of chitosan adsorption for different heavy metals is influenced by the chemical properties

of the metal ions, including their ionic radius, charge density, electronegativity, and coordination preferences. According to the Hard and Soft Acid-Base (HSAB) theory, the amino groups on chitosan act as borderline Lewis bases that have a stronger affinity for borderline acid metal ions such as Cu(II) , Ni(II) , and Zn(II) (Igberase and Mkhize, 2025). Figure 6 illustrates the three primary adsorption mechanisms.

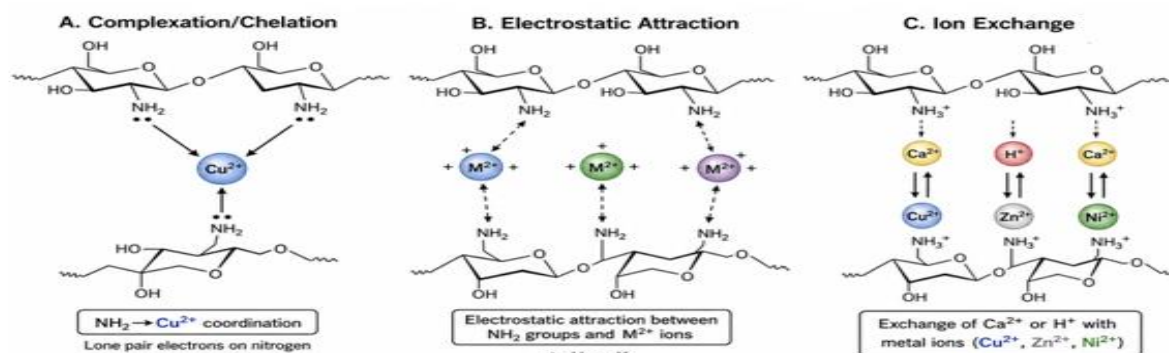


Figure 6. Adsorption mechanisms of heavy metals on chitosan: (A) Complexation/Chelation – coordination of metal ions with amino ($-\text{NH}_2$) and hydroxyl ($-\text{OH}$) groups; (B) Electrostatic attraction – attraction between deprotonated functional groups and metal cations; (C) Ion exchange – replacement of exchangeable ions by heavy metal ions.

The selectivity sequence of chitosan for divalent metal cations has been established as $\text{Cu}^{2+} \gg \text{Hg}^{2+} > \text{Zn}^{2+} > \text{Cd}^{2+} > \text{Ni}^{2+} > \text{Co}^{2+}$ based on competitive adsorption studies (Peris *et al.*, 2021). Complexation/chelation is generally considered the dominant mechanism, where the lone pair electrons on nitrogen atoms of amino

groups coordinate with the empty d-orbitals of transition metal ions to form stable chelate complexes. Electrostatic attraction occurs when protonated amino groups ($-\text{NH}_3^+$) attract metal-containing anionic species. Ion exchange involves the replacement of exchangeable cations (H^+ , Ca^{2+} , Na^+) on the chitosan surface by heavy metal cations (Shahraki *et al.*, 2020).

3.7 Arthropod/Mollusc-Driven Chitosan for Heavy Metal Adsorption

Figure 7 illustrates the application of chitosan derived from arthropod and mollusc sources for the removal of heavy metal ions from water through adsorption.

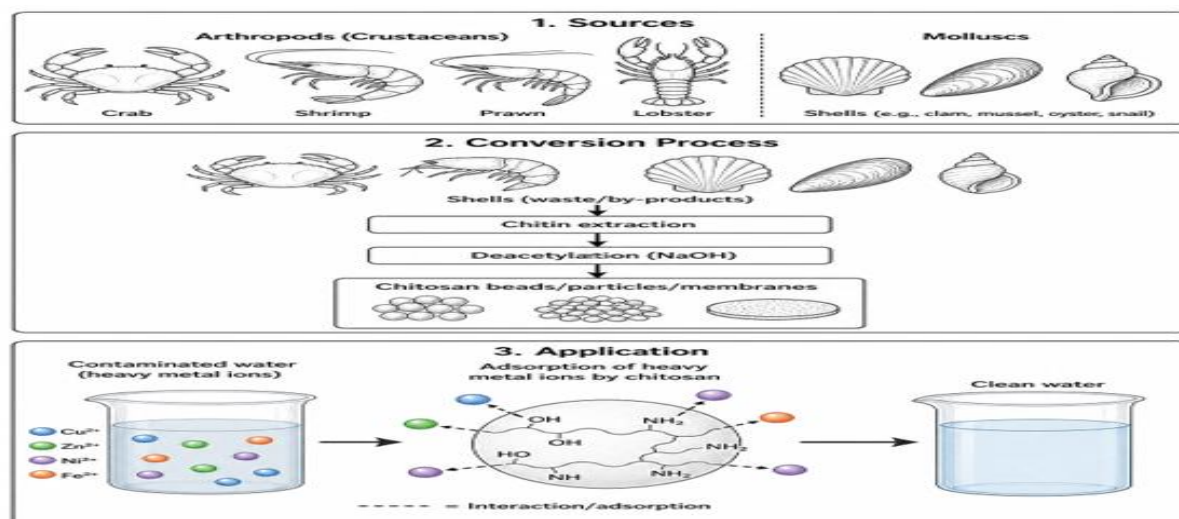


Figure 7. Arthropod/mollusc-driven chitosan for removing heavy metal ions from water through adsorption. Schematic showing sourcing of chitosan from crustaceans (crabs, shrimp, prawns, lobsters) and molluscs, conversion from chitin to chitosan, and application in heavy metal adsorption.

Figure 7 presents a comprehensive schematic showing the sourcing of chitosan from arthropods (crabs, shrimp, prawns, lobsters) and molluscs, the conversion process from chitin to chitosan, and the subsequent application in heavy metal ion adsorption from contaminated water. The abundance of crustacean shell waste from seafood processing industries provides a sustainable and low-cost feedstock for chitosan production, making this approach economically viable for large-scale implementation (Pakizeh *et al.*, 2021; Koirala *et al.*, 2024; Kowanga *et al.*, 2025).

3.8 Characteristics of Chitosan and Heavy Metal Adsorption Capacity

Figure 8 illustrates the relationship between chitosan characteristics and their influence on heavy metal adsorption capacity.

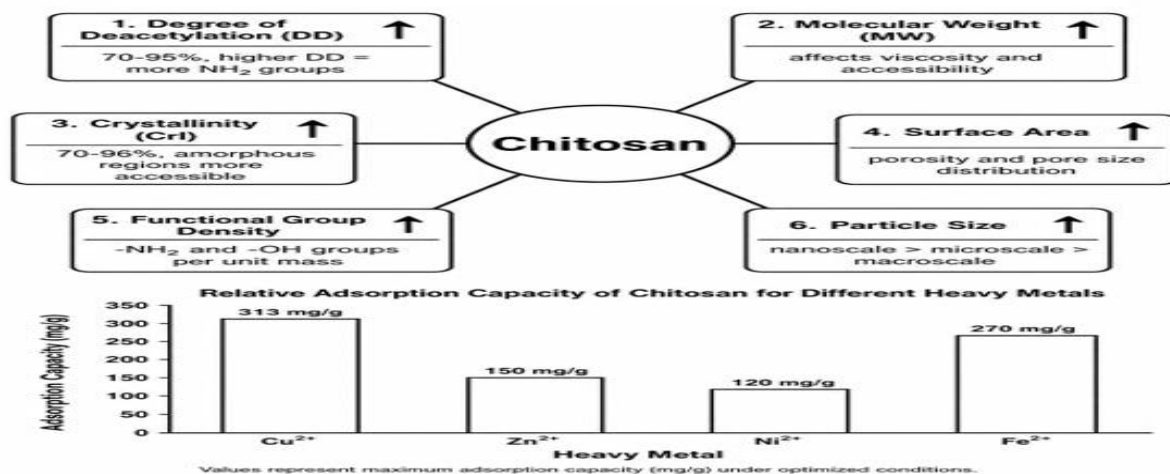


Figure 8. Chitosan characteristics influencing heavy metal adsorption capacity: degree of deacetylation (DD), molecular weight, crystallinity (CrI), surface area, porosity, and functional group density.

Figure 8 presents the key characteristics of chitosan that influence its heavy metal adsorption capacity, including degree of deacetylation, molecular weight, crystallinity, surface area, porosity, and functional group density. The degree of deacetylation (DD) is one of the most critical parameters, as higher DD values correspond to more free amino groups available for metal coordination (Czajkowska *et al.*, 2026). Chitosan with DD above 85% is classified as high DD chitosan

and generally exhibits superior adsorption capacity (Tavares *et al.*, 2020).

3.9 Chitosan Modification Techniques for Heavy Metal Adsorption

Figure 9 illustrates the various modification techniques employed to enhance chitosan's adsorption capacity for heavy metals.

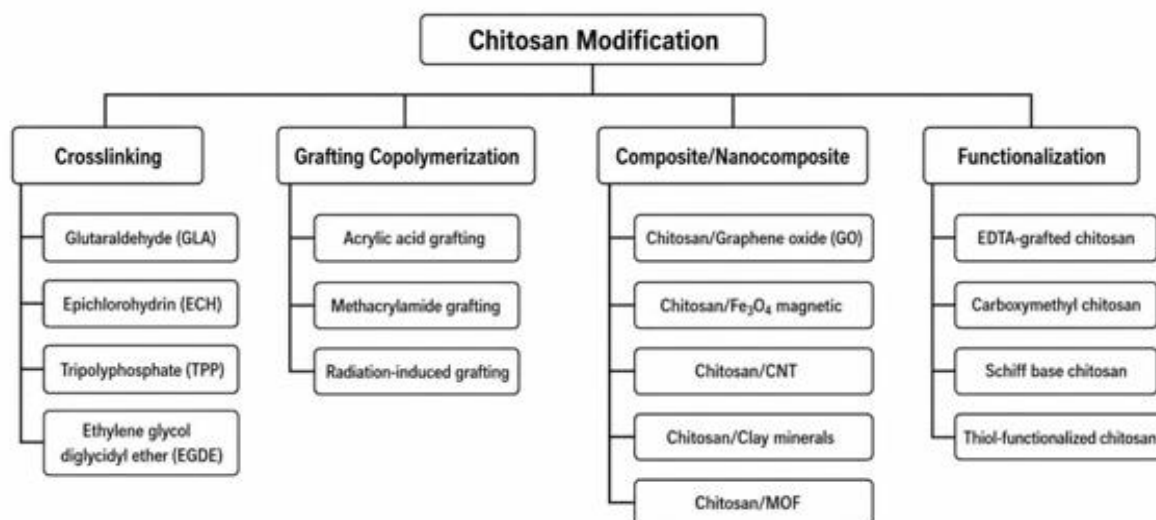


Figure 9. Chitosan modification techniques for adsorption of heavy metals: crosslinking, grafting copolymerization, composite/nanocomposite formation, and functionalization with chelating agents.

Figure 9 presents the major modification strategies for chitosan, which include crosslinking, grafting copolymerization, composite/nanocomposite formation, and functionalization with specific chelating agents (Marrakchi *et al.*, 2020; Igberase and Mkhize, 2025). Crosslinking involves the use of chemical crosslinkers such as glutaraldehyde, epichlorohydrin, ethylene glycol diglycidyl ether, or triphosphosphate to create inter-chain bonds that improve the chemical stability and mechanical strength of chitosan (Barbosa *et al.*, 2025).

Grafting copolymerization involves the attachment of functional monomers or polymers onto the chitosan backbone using chemical initiators or radiation (Nasir *et al.*, 2018). Composite formation involves combining chitosan with other materials such as graphene oxide, carbon nanotubes, magnetic nanoparticles (Fe_3O_4), metal-organic frameworks, clay minerals, or metal oxides (Zhu *et al.*, 2022; Eltaweil *et al.*, 2021; Chadha *et al.*, 2022). Functionalization with chelating agents such as EDTA, dimercaptosuccinic acid, and Schiff bases introduces highly selective metal-binding groups (Zubir *et al.*, 2022; Alhalili and Abdelrahman, 2024; Azizinezhad, 2024).

3.1 Factors Influencing Chitosan Adsorption

3.10.1 Effect of pH

Solution pH is the most critical parameter affecting heavy metal adsorption onto chitosan. At low pH values (below 4), the amino groups on chitosan become protonated ($-\text{NH}_3^+$), creating a positively charged surface that repels metal cations (Zubir *et al.*, 2026). As pH increases, the amino groups become deprotonated ($-\text{NH}_2$), making lone pair electrons available for coordination with metal cations. The optimal pH for Cu(II) adsorption is typically between 5 and 6, while Ni(II) and Zn(II) adsorption is optimal at pH 5 to 7 (Sopanrao *et al.*, 2023; Igberase and Mkhize, 2025).

3.10.2 Effect of Temperature

Temperature influences both the kinetics and thermodynamics of the adsorption process. Most studies report that heavy metal adsorption onto chitosan is endothermic, with adsorption capacity increasing with temperature up to an optimum value 23 to 45 °C (Hu *et al.*, 2023). Thermodynamic studies typically show negative Gibbs free energy changes (indicating spontaneity) and positive enthalpy changes (confirming endothermic nature) for metal adsorption on chitosan (Igberase and Mkhize, 2025).

3.10.3 Effect of Contact Time

The rate of heavy metal adsorption onto chitosan is typically rapid in the initial stages due to the abundance of available surface binding sites, followed by a gradual decrease as equilibrium is approached.

Equilibrium is typically attained within 20 to 180 minutes (Sopanrao *et al.*, 2023). Nanoscale chitosan particles generally reach equilibrium faster than conventional chitosan due to their larger surface area and shorter diffusion path lengths (Benettayeb *et al.*, 2023).

3.10.4 Effect of Adsorbent Dosage

Increasing the adsorbent dosage generally increases the percent removal of heavy metals due to the greater number of available binding sites. However, the adsorption capacity per unit mass may decrease at higher dosages due to particle aggregation and the presence of unsaturated binding sites (Igberase and Mkhize, 2025). Optimal dosages typically range from 0.5 to 5.0 g/L.

3.10.5 Effect of Initial Metal Concentration

The initial metal concentration influences both the adsorption capacity and removal efficiency. At higher initial concentrations, the adsorption capacity (mg/g) typically increases due to the greater driving force for mass transfer, while the percent removal may decrease as the available binding sites become saturated (Moniret *et al.*, 2024).

4.0 CONCLUSION

Chitosan-based adsorption represents a sustainable, cost-effective, and highly promising approach for the removal of heavy metals from electroplating wastewater. The abundance of crustacean shell waste as a renewable feedstock, combined with the excellent adsorption properties of chitosan, positions this biopolymer as a viable alternative to conventional treatment technologies. This comprehensive review has demonstrated that chitosan and its modified forms can effectively remove Cu(II), Zn(II), Ni(II), and Fe(II/III) from aqueous solutions, with adsorption capacities ranging from tens to several hundred milligrams per gram, depending on the adsorbent type and operating conditions.

The characterization of chitosan using FTIR, XRD, SEM-EDS, TGA, XRF, and textural property analysis provides essential information for understanding the structure-property relationships that govern adsorption performance. The predominant adsorption mechanisms include complexation/chelation, electrostatic attraction, and ion exchange, with the amino and hydroxyl functional groups on the chitosan backbone serving as the primary binding sites for metal ions.

Chemical modification through crosslinking, grafting copolymerization, composite formation, and functionalization has been shown to significantly enhance the adsorption capacity, selectivity, and stability of chitosan-based adsorbents. The development of nanoscale chitosan materials, magnetic

chitosan composites, and chitosan-based membranes represents promising directions for advancing the practical applicability of chitosan in heavy metal remediation.

5.0 FUTURE RESEARCH DIRECTIONS

First, the development of selective chitosan-based adsorbents for specific heavy metals in multi-metal systems is critical for practical applications where wastewater contains complex mixtures of contaminants.

Second, the optimization of regeneration and reuse protocols is essential for improving the economic viability and sustainability of chitosan-based treatment systems. Reusability studies have shown that chitosan-based adsorbents can be regenerated and reused for 3 to 10 consecutive adsorption-desorption cycles while maintaining acceptable removal efficiencies (Sopanrao *et al.*, 2023; Zhu *et al.*, 2022). The desorption efficiency typically decreases with increasing cycle number, with a reduction of approximately 10 to 25% in adsorption capacity after 5 cycles (Shahraki *et al.*, 2020).

Third, the development of continuous-flow adsorption systems using chitosan-based membranes, columns, or fixed-bed reactors is essential for scaling up from batch laboratory studies to industrial applications. Research on breakthrough curve analysis and column design optimization is needed to facilitate this transition.

Fourth, life cycle assessment and techno-economic analysis of chitosan-based adsorption systems compared to conventional treatment technologies would provide valuable insights into the environmental and economic sustainability of this approach, supporting decision-making by industrial stakeholders and regulatory authorities.

Fifth, the exploration of alternative, non-crustacean sources of chitosan, including fungal biomass, insect exoskeletons, and agricultural waste, could expand the raw material base and reduce dependence on seasonal seafood industry waste.

Finally, the development of integrated treatment systems that combine chitosan adsorption with other technologies such as membrane filtration, electrochemical treatment, or biological processes could provide comprehensive solutions for the complex wastewater streams generated by the electroplating industry.

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