UTILIZATION OF CHITOSAN IN BIOSORPTION TECHNOLOGY: A REVIEW OF ADSORPTION CAPACITY AND ITS APPLICATIONS FOR HEAVY METALS

Bella Meicyntia[1], Hilfi Pardi[1,*], Ramadhani Muhammad Rizky[2], Ramadani Putri [3]

[1] Department of Chemistry,
Faculty of Engineering and Maritime Technology, Raja Ali Haji Maritime University
Senggarang, Tanjungpinang 29100, Indonesia

[2] Department of Chemistry,
Faculty of Engineering and Maritime Technology, Raja Ali Haji Maritime University
Senggarang, Tanjungpinang 29100, Indonesia

[3] Department of Chemistry,
Faculty of Engineering and Maritime Technology, Raja Ali Haji Maritime University
Senggarang, Tanjungpinang 29100, Indonesia

*corresponding author: hilfipardi@umrah.ac.id

Abstract

The rising levels of heavy metal pollution in water bodies present major environmental and public health issues. Conventional methods for remediation often come with high costs and produce secondary waste, which can pose additional environmental risks. As an alternative, chitosan—a natural, biopolymer derived from chitin—has gained attention as a promising biosorbent for heavy metal removal. Its advantages include biocompatibility, biodegradability, and a strong ability to bind metal ions effectively. This review explores chitosan's capacity to adsorb various heavy metals and examines its practical applications in biosorption technology. Key factors that impact its adsorption efficiency, such as solution pH, metal concentration, and contact time, are discussed. Additionally, structural modifications to enhance chitosan's performance, including cross-linking and nanoparticle incorporation, are analyzed to highlight improvements in adsorption efficiency. By assessing these elements, this review aims to offer a comprehensive perspective on the role of chitosan in environmental management, particularly for treating heavy metal contamination in wastewater. The findings underscore chitosan's potential as a sustainable solution in pollution control, emphasizing its advantages over traditional methods and its capacity to contribute to cleaner water resources.

Keywords: adsorption capacity, biosorption mechanisms, environmental remediation, heavy metal, wastewater treatment

INTRODUCTION

Heavy metal pollution has become an escalating environmental problem across the globe, primarily resulting from industrial activities, mining operations, and agricultural runoff. These anthropogenic actions release significant amounts of toxic metals into the environment, contaminating water bodies, soils, and air (e.g., Briff et al., 2020). Heavy metals, including lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), pose substantial risks not only to human health but also to ecosystems. These metals persist in the environment, do not degrade, and are prone to bioaccumulation in organisms, ultimately leading to biomagnification through the food chain (e.g., Akhtar et al., 2021). The impact of heavy metal pollution is, therefore, a critical issue that demands effective remediation strategies (e.g., Zhang et al., 2022).

The human and environmental health risks associated with heavy metals are welldocumented. In humans, chronic exposure to metals like lead and cadmium can lead to severe neurological, renal, and developmental issues. Similarly, arsenic exposure is known to cause cancers and skin lesions, while mercury affects the nervous and immune systems. In aquatic ecosystems, heavy metals can disrupt reproductive cycles, reduce biodiversity, and impair the function of various organisms, destabilizing entire ecosystems. These pollutants are persistent and non-biodegradable, posing long-term threats that accumulate over time if left untreated. As such, there is an urgent need for efficient and environmentally-friendly methods to remove heavy metals from contaminated water sources (e.g., Ojha et al., 2024).

Biosorption has emerged as a promising solution for heavy metal removal from wastewater, leveraging natural materials with high affinity for metal ions. This process involves using biological substances to bind and absorb heavy metals, offering an eco-friendly and cost-effective alternative to conventional chemical and physical methods of wastewater treatmen (e.g., Priya et al., 2022). One such material, chitosan, has gained particular attention due to its effectiveness as a biosorbent. Derived from chitin, which is found in the exoskeletons of crustaceans like shrimp and crabs, chitosan is abundantly available and has excellent metal-binding properties, making it a sustainable choice for large-scale application (e.g., Raji et al., 2023)

Chitosan’s utility in heavy metal adsorption lies in its unique chemical structure, which contains numerous functional groups, including amino and hydroxyl groups. These groups provide active sites for binding metal ions, enabling effective removal of various heavy metals from aqueous solutions (e.g., Basem et al., 2024). Additionally, chitosan is non-toxic, biodegradable, and has a high adsorption capacity, further enhancing its suitability for biosorption (e.g., Eivazzadeh-Keihan et al., 2020). Over the years, researchers have explored modifications to chitosan’s structure to improve its adsorption efficiency, such as cross-linking, grafting, and nanoparticle incorporation, which increase its stability and metal-binding capacity (e.g., Radha et al., 2021)

This review examines the role of chitosan in biosorption technology, focusing on its adsorption capacity and applications for heavy metal removal. The analysis covers advancements in chitosan-based biosorbents, including modifications that enhance their efficacy in diverse environmental settings. Furthermore, the review discusses challenges associated with the use of chitosan, such as regeneration and reusability, and considers future research directions to optimize its performance in real-world wastewater treatment applications. Through this examination, chitosan is highlighted as a promising, sustainable material in the ongoing efforts to address heavy metal pollution, providing insights into its potential to support cleaner and safer water resources globally (e.g., Saraswati et al., 2020).

METHOD

A systematic literature review was conducted to examine the efficacy of chitosan as a biosorbent for heavy metal removal, utilizing several reputable databases: ScienceDirect, SpringerLink, and Google Scholar. This review focused on peer-reviewed studies published from 2010 to 2024 to ensure recent advancements in biosorption technology were thoroughly examined. Search terms employed included combinations of keywords such as "chitosan," "heavy metal biosorption," "adsorption capacity," "biosorption mechanisms," and "environmental applications," aiming to capture a comprehensive view of chitosan's role and potential in heavy metal remediation (e.g., Rahman et al., 2024).

Studies selected for analysis met specific criteria: they assessed chitosan's adsorption capacity for various heavy metals, investigated factors affecting adsorption efficiency, and explored practical applications in environmental remediation. This included studies on structural modifications to chitosan, such as cross-linking and functional group enhancement, to improve its performance in diverse water treatment contexts (e.g., Francis et al., 2023).

Data extracted from these studies were meticulously analyzed to identify consistent patterns and significant findings related to chitosan’s adsorption efficiency (e.g., Kaczorowska et al., 2024). The review synthesizes key insights into the mechanisms by which chitosan adsorbs metal ions, factors such as pH, contact time, and metal concentration that influence its performance, and its practical applications in real-world environmental management (e.g., Rukhsar et al., 2024). Through this approach, the review aims to highlight chitosan's viability as a sustainable biosorbent solution for addressing heavy metal pollution in contaminated water bodies (e.g., Ayach et al., 2024).

RESULT AND DISCUSSION

3.1 Properties of Chitosan

Chitosan is characterized by its high molecular weight and the presence of amino and hydroxyl functional groups. These properties contribute to its effectiveness in metal ion binding, making it an attractive biosorbent for heavy metal remediation (Chauhan S., 2015).

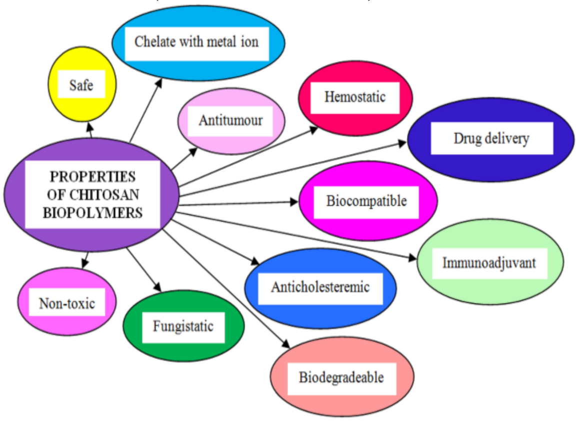

Figure 1. Recent advances of chitosan-based polymers in biomedical applications and environmental protection (e.g., Fatullayeva et al., 2022).

3.2 Adsorption Capacity for Heavy Metals

Chitosan has demonstrated varying adsorption capacities for different heavy metals. Research indicates that chitosan can effectively remove metals such as lead, cadmium, copper, and nickel, with reported capacities ranging from 30 mg/g to over 600 mg/g, depending on the source and processing of chitosan. Factors such as initial concentration, pH, and temperature significantly influence the biosorption process.

Table 1. Adsorption Capacity for Heavy Metals

Alg-EDTA	Initial Concentration (mM)		Adsorption (%)		Adsorption Capacity (mg/g)	
In deionized water	1.5 (Cd^{2+})	-	96.3	-	80.8	-
	1.5 (Pb^{2+})	-	95.6	-	157.0	-
	1.5 (Cu^{2+})	-	93.8	-	47.1	-
	1.5 (Zn^{2+})	-	70.8	-	32.3	-
	1.5 (Co^{2+})	-	84.8	-	37.8	-
	1.5 (Cr^{3+})	-	85.5	-	33.3	-
	1.5 (Cd^{2+})	1.5 (Co^{2+})	87.0	69.5	73.0	30.8
	1.5 (Cd^{2+})	1.5 (Zn^{2+})	85.9	60.3	72.3	29.5
	1.5 (Cd^{2+})	1.5 (Pb^{2+})	90.4	82.5	76.0	135.5
	1.5 (Cd^{2+})	1.5 (Cu^{2+})	90.2	80.9	75.8	40.5
	1.5 (Cd^{2+})	1.5 (Cr^{3+})	85.1	74.8	71.3	29.3
In tap water	1.5 (Cd^{2+})	-	93.7	-	78.8	-
	1.5 (Cd^{2+})	1.5 (Pb^{2+})	91.1	85.5	76.5	140.5
In pond water	1.5 (Cd^{2+})	-	91.2	-	76.5	-

3.3 Mechanisms of Biosorption

The mechanisms underlying heavy metal biosorption by chitosan include:

- Exchange of metal ions with protons on the chitosan surface.
- Formation of stable metal complexes with chitosan’s functional groups.
- Interaction between positively charged chitosan sites and negatively charged metal ions, particularly in acidic conditions.

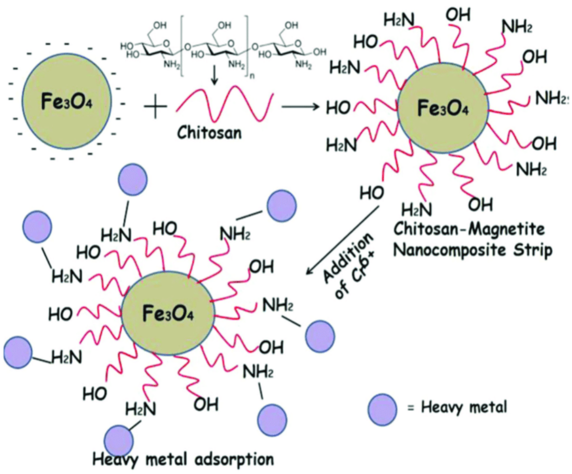

Figure 2. These mechanisms are vital for understanding how chitosan effectively binds heavy metals and can guide optimization of biosorption processes.

3.4 Factors Influencing Adsorption Efficiency

Several key parameters affect the biosorption capacity of chitosan:

- The solution pH significantly influences metal ion availability and chitosan's charge, with optimal adsorption typically occurring at lower pH levels.
- Sufficient contact time is necessary for maximum adsorption, with most studies reporting equilibrium within 60 to 180 minutes.
- Higher temperatures can enhance diffusion rates and adsorption capacities due to increased kinetic energy.

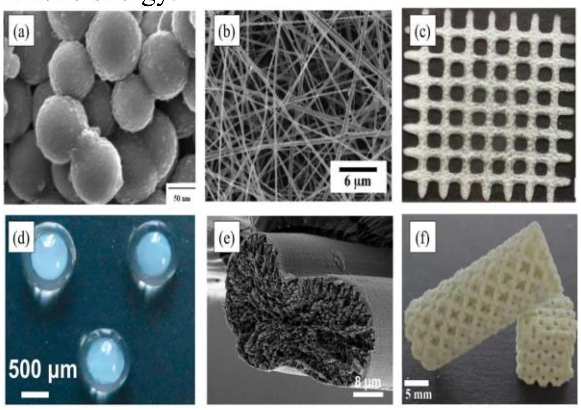

Figure 3. Chitosan: (a) nanoparticles; (b) nanofibers; (c) hydrogel; (d) microspheres (e) fibers; (f) porous. A Review of Chitosan and Chitosan Nanofiber: Preparation, Characterization, and Its Potential Applications (e.g., Ibrahim et al., 2023)

3.5 Modifications to Enhance Chitosan Performance

Various modifications to chitosan have been explored to enhance its biosorption capacity, including:

- Incorporating functional groups to improve metal binding sites.
- Enhancing surface area and porosity through techniques such as freeze-drying or grafting.
- Developing chitosan-based composites with materials like activated carbon or metal oxides to improve overall adsorption performance.

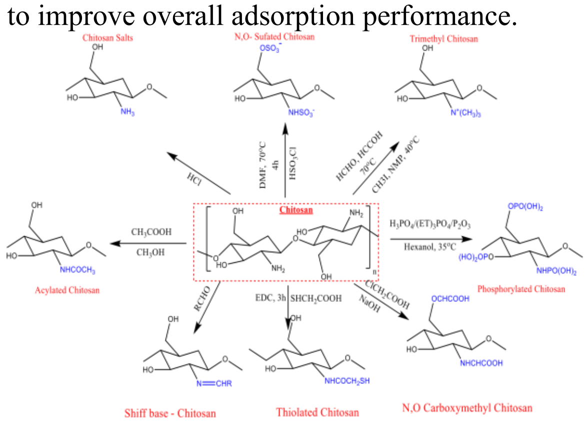

Figure 4. This shows how chitosan can be modified for different applications, such as in biomedicine, pharmaceuticals, and industry.
These modifications can lead to increased efficiency and stability of chitosan as a biosorbent.

3.6 Applications in Environmental Management

Chitosan has been applied in various biosorption processes, including:

- Removal of heavy metals from industrial effluents.
- Stabilization and immobilization of heavy metals in contaminated soils.
- Potential use in removing trace heavy metals from drinking water sources.

Figure 5. Insights into recent advances of chitosan-based adsorbents for sustainable removal of heavy metals and anions (e.g., Omer et al., 2022).

CONCLUSION

Chitosan has emerged as a highly promising biosorbent for removing heavy metals from contaminated water, attributed to its distinct properties, including biocompatibility, biodegradability, and a high capacity to bind metal ions. Its molecular structure, rich in amino and hydroxyl groups, provides multiple active sites for metal ion interactions, making it particularly effective in adsorbing metals such as lead, cadmium, and mercury. These qualities not only support environmental safety but also make chitosan a sustainable choice for large-scale water treatment applications.

Understanding the factors that influence chitosan's adsorption efficiency is essential for optimizing its performance in real-world applications. Key factors such as solution pH, initial metal ion concentration, contact time, and temperature significantly affect chitosan's capacity to adsorb heavy metals. For instance, studies have shown that optimal pH levels can enhance the availability of binding sites, while high metal concentrations may reduce adsorption due to competition for these sites. Therefore, controlling these parameters is critical for maximizing the effectiveness of chitosan-based biosorption systems.

Exploring modifications to chitosan has become a major research focus aimed at further enhancing its adsorption capacity and stability. Techniques such as cross-linking, grafting functional groups, and nanoparticle incorporation have demonstrated improvements in the material's mechanical strength, surface area, and binding efficiency. These modifications can make chitosan more resilient to diverse environmental conditions, allowing for its repeated use and enhanced performance in contaminated waters with varying metal ion compositions.

Continued research and innovation in chitosan-based biosorption technology have the potential to significantly advance sustainable solutions for heavy metal pollution. By developing chitosan into a more versatile and efficient biosorbent, researchers can contribute to safer, cleaner water resources, ultimately supporting environmental protection and public health.

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