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Review

Biosorption of Heavy Metals Using Biomass-Derived Adsorbents: Mechanisms, Modifications, and Future Perspectives

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Abstract

Heavy metals (HMs) pollution of water is a severe global challenge. This review uniquely synthesizes recent advances in using processed agricultural and industrial biomass wastes as low-cost, eco-friendly adsorbents specifically targeting nickel, cobalt, and chromium removal. We systematically analyze how simple chemical and physical treatments significantly enhance metal-binding capacities, often achieving near-complete removal in laboratory settings. Furthermore, emerging bio-nanocomposites combining biomass with metal oxides demonstrate superior multifunctional performance. Crucially, this work integrates detailed discussions on adsorption mechanisms, isotherms, kinetics, thermodynamics, and regeneration strategies through comprehensive tables and schematic diagrams, offering a holistic framework that has not been previously compiled. Despite promising lab-scale results, translating these materials to real-world water treatment faces major challenges including scalable production, complex wastewater interactions, and adsorbent recovery. Addressing these requires interdisciplinary research focused on scalable engineering, cost-effective regeneration, and full environmental impact assessments. By bridging fundamental biosorption science with practical application barriers, this review provides timely, impactful insights to guide future research and promote sustainable water remediation technologies.

Keywords

Agricultural waste, Heavy metal removal, Biomass modification, Wastewater treatment, Sustainable adsorbents

Article History

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1. Introduction

1.1 Background

Water pollution by heavy metals (HMs) such as Nickel (Ni), Cobalt (Co), and Chromium (Cr) has become a pervasive environmental concern globally [1-3]. These HMs, originating from diverse anthropogenic activities including mining, electroplating, textile manufacturing, and chemical industries, are highly toxic, non-biodegradable, and tend to accumulate in living organisms [4]. Their presence in water bodies threatens aquatic ecosystems, contaminates drinking water sources, and poses severe health risks to humans, such as carcinogenicity, organ damage, and neurological disorders [5,6]. Addressing the contamination caused by HMs is therefore critical to protecting both environmental and public health [7-9].

Traditional methods for HMs removal, including chemical precipitation, ion exchange, membrane filtration, and reverse osmosis, have been widely applied (Figure 1). However, these approaches often suffer from limitations such as high operational costs, production of secondary sludge, incomplete removal, and lack of selectivity toward specific metals [10,11]. Additionally, many conventional technologies require sophisticated infrastructure and intensive energy inputs, making them less feasible for large-scale or resource-constrained settings [12,13]. Consequently, there is an urgent need for cost-effective, sustainable, and environmentally benign remediation technologies capable of efficiently removing HMs from wastewater [14-17].

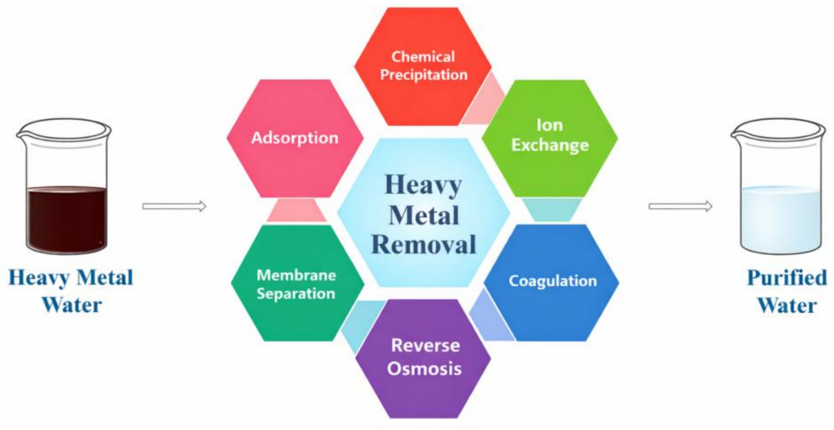

Figure 1. Schematic representation of key technologies employed for HMs removal from wastewater.

Biosorption, defined as the use of biological materials to adsorb and concentrate HMs from water, has gained attention as a sustainable and eco-friendly alternative. Biomass-derived biosorbents such as fruit peels, plant residues, and aquatic weeds are abundant, renewable, and biodegradable, containing functional groups (carboxyl (-COOH), hydroxyl (-OH), amino ($-NH_2$)) that facilitate metal binding via ion exchange and complexation [18-20]. Their low cost and high adsorption capacity make them especially suitable for wastewater treatment in developing regions [21-23].

Recent advances in biomass modification chemical (acid/base), physical (thermal), and biological (enzymatic) treatments have enhanced surface area, porosity, and active binding sites, improving adsorption efficiency and selectivity [24-29]. Emerging hybrid materials combining biomass with nanostructures like tungsten oxide further enhance heavy metal removal and photocatalytic degradation [30].

While many reviews cover biomass-derived adsorbents for heavy metal removal, this manuscript offers a focused, up-to-date synthesis on nickel, cobalt, and chromium biosorption. It integrates various biomass modification strategies with mechanistic insights and compiles comprehensive tables on adsorption capacities, isotherm and kinetic models, thermodynamics, and regeneration, alongside diagrams linking modifications to mechanisms. Additionally, the review tackles key challenges like scalability, performance in complex multi-metal wastewaters, and the role of emerging tools such as artificial intelligence (AI) and life cycle assessment (LCA). By connecting fundamental science with practical applications, this work fills critical gaps and serves as a valuable resource for advancing sustainable heavy metal remediation.

This review analyzes biosorption mechanisms, evaluates the effects of biomass modification on adsorption performance, and reviews recent applications targeting Ni (II), Co (II), and Cr (VI) removal. We also discuss challenges in scaling up, managing multi-metal contaminated wastewater, and integrating biosorption with microbial remediation. Finally, future research directions, including AI for adsorbent design and LCA for sustainability, are explored to advance biosorption as a viable pathway for heavy metal remediation in water treatment.

1.2 Regulatory Standards for HMs in Drinking Water

HMs in water threaten health and ecosystems worldwide [31-38]. The World Health Organization (WHO) sets maximum allowable limits in drinking water to prevent adverse effects, from acute poisoning to chronic diseases such as cancer and organ damage [38-47]. Table 1 summarizes these guideline values for key metals like Ni, Co, and Cr. For example, Ni is limited to 0.07 mg/L due to skin and respiratory risks [48]; highly toxic hexavalent chromium (Cr VI) is restricted to 0.05 mg/L because of carcinogenicity and organ toxicity [49]. Co limits are less defined but often set around 0.05 mg/L as a precaution [50]. These standards provide benchmarks for biosorption effectiveness, requiring treated effluents to meet safety thresholds [51]. Hence, biosorbent development must focus on achieving regulatory compliance alongside maximizing removal efficiency, especially in regions with industrial pollution and water scarcity [52].

Table 1. WHO guidelines for maximum allowable concentrations of selected HMs in drinking water and associated health effects.

HMs	Chemical Form	WHO Maximum Limit (mg/L)	Health Effects
Nickle (Ni)	Ni^{2+}	0.07	Skin allergies, respiratory problems, potential carcinogen
Cobalt (Co)	Co^{2+}	0.05*	Possible carcinogenic effects; limited data
Chromium (Cr)	Cr (VI) (Hexavalent)	0.05	Carcinogenic, respiratory issues, kidney and liver damage
Lead (Pb)	Pb^{2+}	0.01	Neurotoxicity, especially in children
Cadmium (Cd)	Cd^{2+}	0.003	Kidney damage, bone demineralization
Mercury (Hg)	Hg^{2+}	0.006	Neurological and kidney damage

Note: * The guideline value for cobalt is provisional due to limitations in the available toxicological data.

2. Methodology

2.1 Literature Search and Selection Protocol

A systematic search strategy was implemented to identify, select, and synthesize the relevant scientific literature on the biosorption of Ni (II), Co (II), and Cr (VI) using biomass-derived adsorbents. The methodology was designed to ensure comprehensiveness, reproducibility, and transparency, aligning with best practices for evidence synthesis.

2.1.1 Information Sources and Search Strategy

Electronic searches were conducted in two core citation databases, Scopus and Web of Science (Core Collection), on December 2024. To minimize publication bias and locate additional relevant literature, including preprints and theses, a supplementary search was performed in Google Scholar. The search timeframe was limited to publications from January 2000 to December 2024 to focus on contemporary research while capturing foundational studies.

2.1.2 Eligibility Criteria and Study Selection

Retrieved records from all sources were combined, and duplicates were removed using a reference management software (EndNote, Clarivate Analytics). The subsequent screening involved two sequential stages:

(1) Title/abstract screening. Two independent reviewers screened titles and abstracts against initial inclusion criteria: (a) focus on the aqueous-phase adsorption of Ni (II), Co (II), or Cr (VI); (b) use of a primary adsorbent material derived from biomass or organic waste; (c) presentation of original experimental data.

(2) Full-text assessment. The full texts of potentially eligible studies were retrieved and subjected to a detailed appraisal based on predefined criteria. Studies were excluded if they: (a) utilized exclusively synthetic or inorganic adsorbents (e.g., engineered nanomaterials, zeolites) without a biomass component; (b) lacked essential quantitative performance data (e.g., adsorption capacity, removal percentage, fitted model parameters); (c) were non-primary literature (e.g., review articles, editorials, book chapters); or (d) were not available in English. Conflicts between reviewers were resolved through discussion or consultation with a third author.

2.1.3 Data Extraction and Synthesis

Data from the final set of included studies were extracted into a structured Microsoft Excel® spreadsheet. Extracted variables encompassed: (a) Adsorbent properties: Biomass source, type, and modification method; (b) Experimental conditions: Target metal, initial concentration, solution pH, temperature, adsorbent dose; (c) Mechanistic insights: Dominant adsorption mechanism(s) proposed; (d) Practical considerations: Data on adsorbent regeneration, reusability, and application in real or synthetic multi-metal wastewater. This structured dataset formed the basis for the comparative analysis and narrative synthesis presented in this review.

2.2 Screening and Selection Criteria

An initial search identified over 250 articles. After removing duplicates and non-peer-reviewed sources, 225 articles remained for screening. Inclusion criteria were: studies on biosorption of HMs (Ni, Co, Cr) using biomass-derived materials; investigations on chemical, physical, or biological biomass modifications to enhance adsorption; reports providing quantitative data on adsorption capacity, removal efficiency, isotherms, and kinetics; studies addressing biosorbent regeneration, reusability, and scalability; and English-language full-text articles. Excluded were studies focusing solely on synthetic or inorganic adsorbents, lacking experimental validation or sufficient data, opinion pieces, reviews without original data, and non-English publications. Following screening, 168 articles were selected for full-text review.

2.3 Data Extraction and Analysis

Data from selected studies were systematically extracted, covering biomass types and origins, modification methods, target HMs and concentrations, adsorption performance (capacity, efficiency, rates), kinetic and isotherm models, regeneration potential, and experimental setups. Challenges like multi-metal interference and scalability were noted. This information was compiled into tables and figures to highlight trends and identify research gaps and emerging technologies.

2.4 Quality Assessment

To ensure the reliability and validity of the findings summarized in this review, each included study underwent a quality appraisal based on: The clarity and reproducibility of experimental methods. Adequacy of controls and replicates. Statistical treatment of data, including error analysis and model fitting quality (e.g., R^2 values). Relevance and practical applicability of biosorption results, particularly in real wastewater scenarios. Preference was given to studies published in high-impact journals, with recent publications prioritized to reflect current scientific understanding and technological advances.

3. Key Technologies Employed for HMs Removal from Wastewater

HMs in wastewater can be treated using physical, chemical, and biological methods, each with distinct advantages and limitations (Figure 2). Chemical precipitation, one of the most common methods, involves adding reagents like lime or sulfides to convert dissolved metals into insoluble forms for removal by sedimentation or filtration [53]. While cost-effective, it generates large volumes of metal-laden sludge requiring careful disposal [54]. Adsorption techniques using materials such as activated carbon, biochar, and nanomaterials offer high removal efficiencies, particularly at low metal concentrations, and allow adsorbent regeneration for improved sustainability [55]. Ion exchange provides selective metal removal via reversible ion substitution but can be hindered by competing ions and requires pretreatment for complex wastewaters [56].

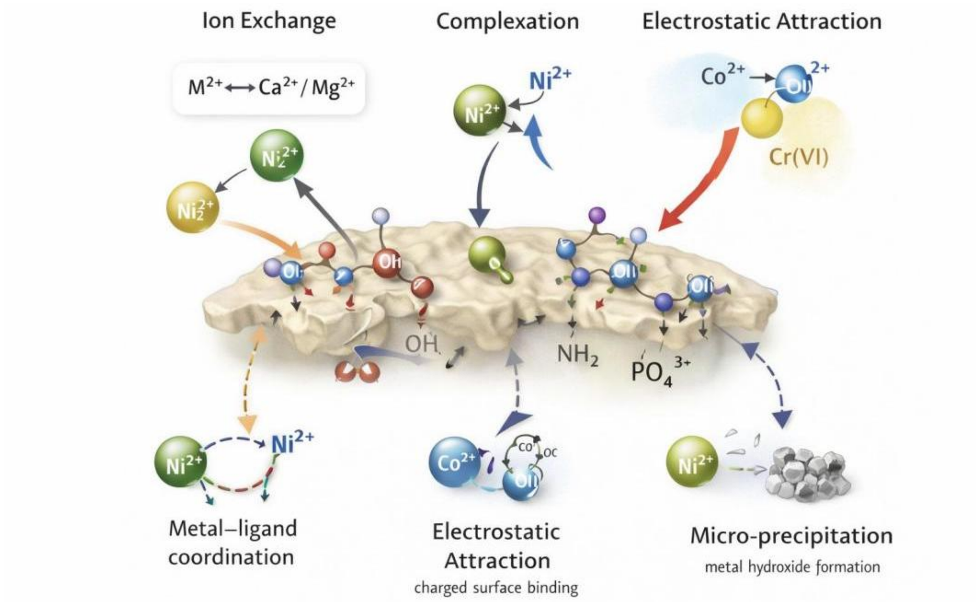

Figure 2. Dominant biosorption mechanisms: ion exchange, surface complexation, electrostatic attraction, micro- precipitation, and physical adsorption on biomass- derived adsorbents.

Advanced physical and biological treatments also contribute. Membrane filtration methods like reverse osmosis and nanofiltration effectively separate metals by size and charge but are energy-intensive and prone to fouling [57]. Electrochemical processes, such as electrocoagulation, destabilize metals using electric current, minimizing chemical use but requiring precise control and maintenance [58]. Biological methods, including phytoremediation and microbial bioremediation, use plants and microorganisms to uptake or transform metals, offering eco-friendly options suitable for low to moderate contamination with slower treatment times [59]. Among these, biosorption is a complex process involving multiple physicochemical mechanismsion exchange, complexation, electrostatic attraction, microprecipitation, and physical adsorption that work synergistically to bind metals to biomass surfaces [60]. Functional groups such as -COOH, -OH, $-NH_2$, and phosphate ($-PO_4^{3-}$) serve as active sites for metal binding [61].

Ion exchange, often dominant under optimized pH and temperature, replaces native cations on the biosorbent with metal ions, influenced by ionic radius, charge, and hydration energy [62]. Complexation forms stable coordination bonds between metal ions and electron-donating groups, creating strong metal-ligand complexes [63-65]. Electrostatic attraction enhances binding when the biosorbent surface is negatively charged, which depends on solution pH affecting functional group ionization [66-70]. Microprecipitation forms insoluble metal precipitates on or within the biosorbent, improving removal but potentially limiting regeneration [71-75]. Physical adsorption provides reversible, weak initial attachment via van der Waals forces, facilitating subsequent stronger chemical binding [76-77]. The overall biosorption efficiency depends on biomass composition, surface area, porosity, and environmental factors such as pH, temperature, and ionic strength [78-80]. Understanding these mechanisms is essential for tailoring biosorbents through chemical or physical modification to enhance capacity and selectivity [81].

In addition to surface interaction mechanisms, adsorption performance is strongly governed by kinetic behavior, equilibrium modeling, thermodynamic feasibility, and regeneration stability as shown in (Table 2), which collectively determine the practical applicability of biosorbents in wastewater treatment systems [82-85]. Most biomass-derived adsorbents follow pseudo-second-order kinetic models, indicating that chemisorption involving electron sharing or exchange between metal ions and surface functional groups governs the rate-limiting step [86-88]. Equilibrium adsorption data are frequently best described by the Langmuir isotherm model, suggesting monolayer adsorption on homogeneous active sites, whereas Freundlich and Temkin models reflect heterogeneous surface interactions and adsorbate-adsorbent energy distributions under certain operating conditions [89,90].

Table 2. Biomass-derived adsorbents, modification methods, adsorption models, thermodynamic behavior, and regeneration performance for heavy metal removal.

Biomass Source	Modification Method	Target HMs	Max Capacity (mg/g)	Kinetics Model	Isotherm Model	Thermodynamics	Regeneration (Cycles/% Retention)	Ref.
Lemon peel	NaOH treated	Ni (II)	36.7	Pseudo-2nd order	Langmuir	$\Delta G < 0$, endothermic	5 cycles/~90%	[9]
Sugarcane bagasse	H_3PO_4 + thermal	Cr (VI)	98.2	Pseudo-2nd order	Langmuir, Temkin	$\Delta G < 0, \Delta H > 0$	6 cycles/88%	[7]
Mango leaf powder	Unmodified	Cr (VI)	99.1	Pseudo-2nd order	Langmuir	Spontaneous	4 cycles/82%	[23]
Mustard biochar	Acid activated	Co (II)	95	Pseudo-2nd order	Langmuir	Endothermic	5 cycles/85%	[21]
Rice husk biochar	Steam activated	Pb (II), Cd (II)	110	Pseudo-2nd order	Freundlich	$\Delta G < 0$	7 cycles/90%	[27]
Polypyrrole/ bagasse	Polymer composite	Cr (VI)	251	Pseudo-2nd order	Langmuir	Endothermic	5 cycles/87%	[2]
Banana peel carbon	Pyrolysis	Co (II)	72	Pseudo-2nd order	Freundlich	Spontaneous	4 cycles/80%	[25]
Biochar-WO_3 composite	Metal oxide doping	Cr (VI)	>100	Mixed	Langmuir	Endothermic	Magnetic recovery	[36]

Thermodynamic parameters further explain adsorption behavior, where negative Gibbs free energy (ΔG) values confirm the spontaneous nature of metal uptake, and positive enthalpy (ΔH) values indicate endothermic adsorption in many biosorbent systems, implying improved performance at elevated temperatures [91-93]. Positive entropy (ΔS) values suggest increased randomness at the solid-solution interface during adsorption [94]. Regeneration and reuse are critical for assessing economic feasibility and environmental sustainability [95]. Desorption using dilute acids, alkalis, or chelating agents commonly restores 70-95% of adsorption capacity over multiple cycles; however, repeated regeneration may gradually reduce performance due to structural degradation or irreversible metal binding [96-100]. Therefore, comprehensive evaluation of adsorption modeling and regeneration behavior is essential for scaling biosorption technologies from laboratory investigations to real-world wastewater treatment applications [101-103].

4. Impact of Biomass Modification on Biosorption Performance

The biosorption capacity of raw biomass can be greatly enhanced through various modification techniques that improve their physical and chemical properties (Figure 2). These modifications including chemical (acidic or alkaline), physical (thermal, microwave), and biological (enzymatic) treatments increase surface area, porosity, and the density and accessibility of functional groups responsible for HMs binding, resulting in improved adsorption performance suitable for practical wastewater treatment [104,105].

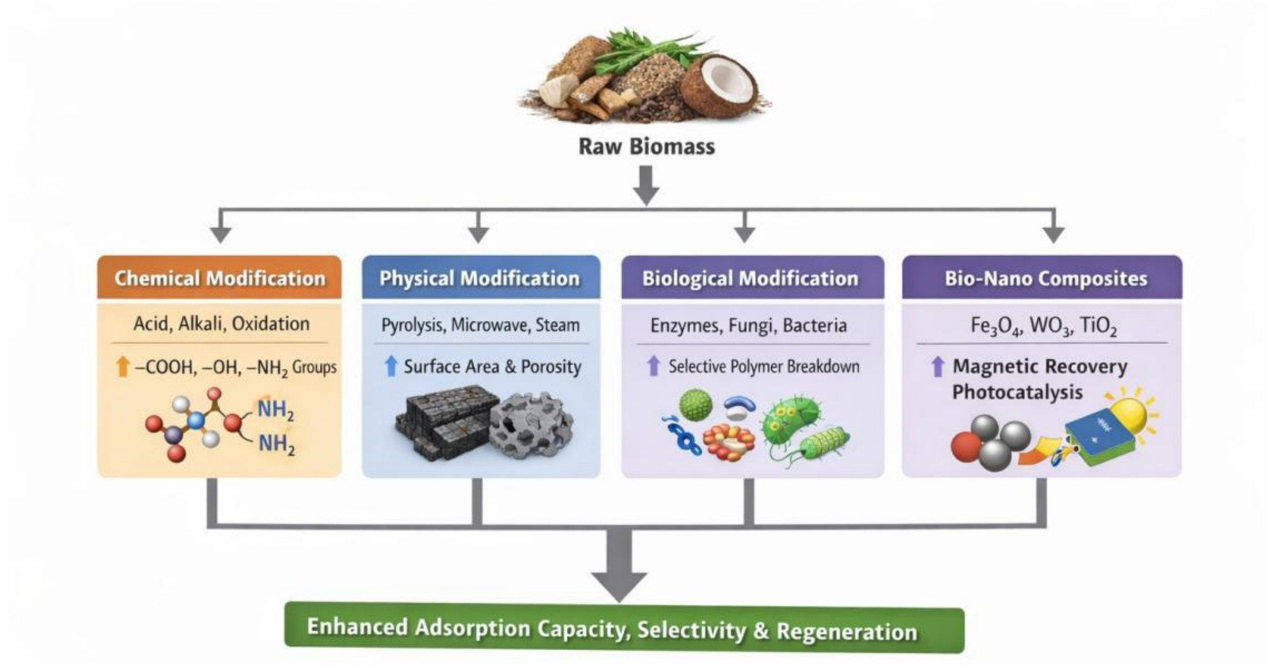

Figure 3. Schematic illustration of major modification strategies applied to biomass-derived adsorbents, including chemical, physical, biological, and bio-nanocomposite approaches.

4.1 Chemical Modification

Chemical treatments are widely used to enhance biosorption by altering surface functional groups and increasing porosity (Figure2) [106,107]. Acid treatments with mineral acids (e.g., HNO_3, H_3PO_4) hydrolyze hemicellulose and lignin, removing impurities and exposing carboxyl, hydroxyl, and phosphate groups, which improves metal binding via electrostatic attraction and complexation [108,109]. Alkaline treatments (NaOH, KOH) swell the biomass matrix and deprotonate acidic groups, generating more negatively charged sites for cation adsorption [110-112]. For example, NaOH-treated lemon peel showed a 2.5-fold increase in Ni (II) adsorption capacity, highlighting the effectiveness of chemical modification [113].

4.2 Physical Modification

Physical methods like thermal activation, microwave irradiation, pyrolysis, and steam activation enhance biomass structure by increasing surface area and pore volume [114,115]. Thermal activation decomposes biomass components, creating a porous, carbon-rich matrix that improves diffusion and adsorption [116,117]. Microwave treatment offers rapid, uniform heating to develop pore networks efficiently [118-120]. Combined chemical-physical modifications, such as phosphoric acid-assisted thermal activation of sugarcane bagasse, synergistically increase adsorption capacity (e.g., Cr (VI) uptake up to 98.15 mg/g) [121]. These physical methods make biosorbents more effective and scalable for industrial use [122].

4.3 Biological Modification

Biological or enzymatic treatments use specific enzymes or microbes to selectively degrade lignin, hemicellulose, and other polymers, increasing surface accessibility and exposing functional groups without harsh chemicals or high temperatures [123-125]. Enzymes like cellulases and lignin-degrading oxidases improve surface roughness and active site availability, while fungi and bacteria can further enhance porosity and introduce new binding sites [126,127]. Though slower and more sensitive to conditions than chemical methods, biological modifications offer eco-friendly alternatives with high selectivity.

4.4 Quantitative Correlations and Mechanistic Insights

Studies reveal strong correlations ($R^2 > 0.95$) between the density of functional groups especially carboxyl groups and metal adsorption capacity, indicating surface chemistry plays a more critical role than surface area alone [128]. Metals bind primarily through deprotonated carboxyl groups forming coordination bonds and ion-exchange interactions, as confirmed by spectroscopic analyses (fourier transform infrared spectroscopy (FTIR), X-ray Photoelectron spectroscopy (XPS), nuclear magnetic resonance (NMR)) [129,130]. These insights underscore the importance of targeted functional group engineering to systematically enhance biosorption efficiency.

4.5 Enhanced Performance in Continuous-Flow Systems

Testing biosorbents in continuous-flow setups (e.g., fixed-bed columns) simulates real wastewater conditions better than batch tests, revealing improved stability, regeneration, and mass transfer kinetics [131]. For example, chemically modified rice husks maintained ~90% Cr (VI) removal efficiency after 10 adsorption-desorption cycles, demonstrating durability and practical viability [132]. Such performance is crucial for reducing costs and waste in industrial applications.

4.6 Synergistic Modifications and Future Directions

Combining multiple modification techniques (chemical, physical, biological) often yields synergistic improvements in surface properties and adsorption capacity [133]. Incorporating nanomaterials like metal oxides (tungsten oxide (WO_3)) into biomass matrices creates multifunctional bio-nanocomposites with enhanced adsorption, photocatalytic reduction, and easy magnetic recovery [134]. Future research should focus on optimizing modification methods for cost-effectiveness, long-term stability, scalability, integration with microbial remediation, and environmental sustainability through LCA to advance real-world applications.

Recent studies emphasize that adsorption efficiency is not governed by surface area alone, but strongly correlates with the density and accessibility of oxygen- and nitrogen-containing functional groups [135]. Spectroscopic evidence from FTIR and XPS confirms that deprotonated carboxyl and amino groups dominate metal binding through coordination and ion-exchange mechanisms [136]. Therefore, rational functional group engineering, rather than excessive thermal activation, is increasingly recognized as the most energy-efficient pathway for enhancing biosorption capacity [137]. This insight supports the design of targeted low-temperature modification techniques suitable for decentralized and resource-limited wastewater treatment applications [138].

5. Application of Biomass-Derived Adsorbents for HMs Removal

Biomass-derived adsorbents have gained widespread attention as sustainable, low-cost solutions for removing HMs from contaminated water. Their abundance, biodegradability, and diverse functional groups enable efficient binding of toxic metals like Ni, Co, and Cr. Additionally, hybrid materials such as WO_3 nanostructures combined with biomass show promising multifunctional remediation properties.

5.1 Nickel

Nickel pollution arises mainly from electroplating, mining, and battery industries, posing serious health risks including carcinogenic and respiratory effects [139]. Biosorption using agricultural waste such as lemon peels, rice husks, and banana peels has shown Ni (II) removal efficiencies often exceeding 90%, sometimes approaching complete removal [140]. Chemical modifications, particularly alkaline treatments with NaOH, significantly boost adsorption capacity by increasing the ionization of functional groups like carboxyl and hydroxyl, enhancing electrostatic attraction and complexation [141]. Adsorption kinetics typically follow a pseudo-second-order model, indicating chemical bonding governs the process, while Langmuir isotherms suggest monolayer adsorption on uniform sites [142]. These characteristics support the practical use of biomass adsorbents for scalable Ni (II) wastewater treatment.

5.2 Cobalt

Cobalt, extensively used in batteries and alloys, can cause cardiotoxicity and genotoxicity when present in excess [143]. Biochar from mustard stalks, algae, and coconut shells effectively removes Co (II), especially after acid activation (e.g., with HNO_3), which enhances surface acidity and functional group exposure. Marine macroalgae and aquatic plants like water hyacinth also provide abundant sulfate, carboxyl, and amino groups that bind Co^{2+} via electrostatic and ion-exchange mechanisms [144]. Co (II) adsorption commonly follows pseudo-second-order kinetics and fits Langmuir isotherms, reflecting chemisorption on homogeneous surfaces [145]. These biosorbents offer a renewable, low-cost option for Co remediation in industrial effluents [146].

5.3 Chromium

Hexavalent chromium Cr (VI) is highly toxic and carcinogenic, requiring efficient removal methods [147-150]. Agricultural wastes such as mango leaves, orange peels, and sugarcane bagasse exhibit high Cr (VI) adsorption efficiencies; mango leaf powder achieves up to 99.13% removal [151]. Modified composites, like polypyrrole-coated sugarcane bagasse, show enhanced capacities (up to 251 mg/g) due to nitrogenous groups facilitating electrostatic and redox interactions [152]. Adsorption fits Langmuir and Temkin isotherms, indicating monolayer coverage and adsorbate-adsorbent interaction effects [153]. Kinetics typically follow a pseudo-second-order model, driven by chemical adsorption coupled with reduction of Cr (VI) to less toxic Cr (III), improving detoxification. These biomass-based adsorbents hold great promise for large-scale Cr (VI) treatment [154].

5.4 Emerging Materials: Tungsten Oxide Nanostructures

While pure biomass adsorbents are effective, their integration with functional nanomaterials can create superior hybrid systems. WO_3 nanostructures, known for their visible-light photocatalysis and high surface area, are particularly promising for creating advanced bio-nano composites. When combined with biomass substrates (e.g., biochar, cellulose), these composites leverage the high adsorption capacity of the biomass with the photocatalytic activity of WO_3, enabling not just adsorption but also the reduction and detoxification of metals like Cr (VI) [155]. Doping with metals (Fe, Ag, Cu) can further enhance functionality, such as adding magnetic recoverability. These hybrids represent a strategic evolution of biomass-derived adsorbents, moving beyond passive adsorption to active, multi-functional remediation [156]. However, challenges in scalable synthesis of the hybrids, nanoparticle stability, and real wastewater performance must be addressed to translate these promising lab-scale materials into practical applications [157-160].

6. Challenges and Future Directions

Despite the promising advances in biomass-derived biosorbents for HMs remediation, several critical challenges remain that hinder the transition from laboratory research to large-scale, practical applications. Addressing these challenges requires multidisciplinary approaches that combine material science, microbiology, environmental engineering, and computational modeling. Below, key challenges and prospective future directions are discussed in detail.

6.1 Scalability and Regeneration

Scaling up biosorption from lab batch studies to continuous-flow industrial systems faces operational hurdles like clogging, pressure drops, and uneven flow, which reduce biosorbent lifespan and raise maintenance costs. For example, sugarcane bagasse in pilot bioreactors showed 90% Cr (VI) removal but suffered clogging after 15 cycles [161]. Modular bioreactor designs can help mitigate these issues by facilitating maintenance and adapting to variable wastewater volumes. Regeneration and reuse remain critical for economic viability; chemically modified biosorbents (e.g., NaOH-treated lemon peels) have demonstrated around 90% capacity retention over multiple cycles under ideal conditions [162]. However, their long-term performance in real wastewater with fluctuating contaminant loads is understudied. Future research should develop environmentally friendly, cost-effective regeneration techniques such as mild chemical or electrochemical methods and integrate biosorption with metal recovery to enhance sustainability.

6.2 Multi-Metal Systems and Real Wastewater Complexity

Most studies focus on single-metal removal in controlled settings, while actual wastewaters contain complex mixtures of metals and organics that compete for adsorption sites, often lowering efficiency. For example, Ni (II) uptake can drop by about 20% when Cr (VI) coexists due to site competition [163]. Natural organic matter, pH variability, and ionic strength further complicate performance. To tackle these challenges, AI and machine learning (ML) models have recently shown promise in predicting competitive adsorption with up to 95% accuracy, guiding selective biosorbent design tailored to complex wastewater [163]. Nonetheless, extensive real wastewater testing and field trials are essential to validate these models and ensure robust performance under dynamic conditions.

6.3 Integration with Microbial Bioremediation

Combining biosorption with microbial bioremediation offers synergistic benefits by coupling metal adsorption with microbial transformation or reduction. For instance, rice husk biochar paired with *Methylococcus capsulatus* achieved up to 95% Cr (VI) detoxification by reducing it to less toxic Cr (III). Developing multifunctional bio-nanocomposites that integrate microbes with modified biomass could harness combined mechanisms of adsorption, enzymatic reduction, and photocatalysis. Optimizing interactions such as biofilm formation and metal bioavailability will be key to advancing these hybrid systems [164].

6.4 Life Cycle Assessment

Though biosorption is generally eco-friendly, comprehensive LCAs are vital to quantify its overall environmental footprint across production, use, and disposal stages. A 2024 LCA revealed rice husk biochar emits about 50% less CO_2 compared to activated carbon, highlighting its sustainability advantage [165]. However, data are scarce on energy-intensive modifications like nanoparticle doping or thermal activation [165]. Balancing performance gains with environmental impacts requires thorough LCA and techno-economic assessments to guide sustainable biosorbent development and inform policies aligned with climate goals.

6.5 AI and Computational Modeling

AI and ML have emerged as promising tools to enhance biosorbent design and optimize treatment processes. Recent studies have demonstrated practical applications of ML models that accurately predict adsorption capacities–for example, achieving up to 95% accuracy in estimating Ni (II) uptake based on parameters such as pH, surface area, and functional group density [166]. These models move beyond conceptual discussions by providing actionable insights for tailoring biosorbent properties and guiding experimental design [167].

Furthermore, integration of AI with real-time monitoring systems in wastewater treatment facilities shows potential to dynamically adjust operational parameters like flow rate, pH, and regeneration cycles, improving treatment efficiency and reducing operational costs [168]. However, challenges remain in developing hybrid modeling frameworks that effectively combine mechanistic understanding with data-driven approaches. To address this, ongoing research is increasingly focused on interdisciplinary collaborations that merge material science, environmental engineering, and computational expertise. Such efforts aim to transition AI-enhanced biosorption technologies from theoretical concepts toward scalable, real-world applications. Future work should also prioritize validating AI models under diverse, complex wastewater conditions to ensure practical robustness and reliability.

7. Conclusion

Biomass-derived biosorbents represent a practical, sustainable, and low-cost solution for the treatment of HM-contaminated wastewater, particularly in regions with abundant agricultural and industrial biomass residues. Their strong metal-binding capability, environmental compatibility, and potential for local production position them as viable alternatives to conventional treatment technologies. While laboratory-scale studies clearly demonstrate their effectiveness, wider adoption requires addressing key challenges related to scalability, performance in real wastewater systems, and long-term operational stability. Future efforts should prioritize the development of simple, locally adaptable modification methods, validation under field conditions, and integration into existing decentralized treatment infrastructures. With targeted research, policy support, and pilot-scale implementation, biomass-based biosorption technologies can play a meaningful role in advancing sustainable water management and protecting public and environmental health.

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Conflict of Interest Statement

The authors confirm that there are no known financial or personal conflicts of interest that could have influenced the findings or interpretations presented in this study.

Generative AI Statement

The author declares that no Generative AI (GenAI) was used in the creation of this manuscript.

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