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Assessing the Efficiency of Plant-Derived Biosorbents in Biosorption of Heavy Metals from Wastewater: A Mini Review

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Abstract: Heavy metals are among the most persistent environmental pollutants, contributing significantly to wastewater contamination and posing severe risks to human health and ecosystems. Industrial activities such as mining, tanning, and manufacturing have accelerated their accumulation beyond permissible limits. Since these metals are non-biodegradable and bioaccumulative, efficient treatment methods are essential. Conventional techniques, including ion exchange, membrane filtration, and chemical precipitation, are widely applied but are often costly and energy-intensive, and they produce secondary pollutants. In contrast, biosorption, which employs low-cost biological materials, has emerged as a promising and sustainable alternative. Plant-based biosorbents, particularly those derived from agricultural wastes such as maize cobs, husks, onion peels, soybean hulls, mango seed and kernel, and coconut husks, have gained significant research attention in recent years due to their availability, renewability, and eco-friendliness. The review highlights that biosorbents exhibit high adsorption capacities for metals such as lead, cadmium, arsenic, and chromium, with performance strongly influenced by surface functional groups, porosity, pH, and biosorbent modification methods. A comparative evaluation shows that certain treated agricultural wastes perform more efficiently under specific conditions. Furthermore, adsorption mechanisms, such as ion exchange, complexation, and precipitation, are discussed in relation to their contributions to removal efficiency. Future research should prioritize scale-up, regeneration, and integration with existing treatment systems to enable real-world application of biosorption.

Keywords: wastewater; heavy metals; biosorption; plant-derived biosorbents.

1. Introduction

Global industrialization has significantly increased levels of hazardous heavy metals in aquatic environments, threatening ecosystem health and all living species [1]. Toxic metals such as mercury, iron, lead, copper, cobalt, chromium, cadmium, zinc, nickel, uranium, and manganese are non-biodegradable and can cross biological barriers, entering the food chain through natural processes such as corrosion, leaching, soil erosion, and volcanic activity [2,3]. However, human activities remain the primary contributors, including mining, farming practices, electroplating, fossil fuel combustion, paper and textile processing, polymer industries, nuclear power plants, waste disposal, and other industrial operations [4]. Common toxic metals such as lead, arsenic, chromium, thallium, cadmium, and antimony contaminate soils and water bodies, forming sediments that impair plant growth by reducing photosynthesis, nutrient uptake, and seed germination [5]. Long-term exposure in humans can damage vital organs, including the skin, heart, kidneys, eyes, and nervous system, and may also cause cancer and developmental disorders in children [6,7]. Biosorption is a process that uses biological materials to remove contaminants. Biosorption is a flexible approach to eradicate heavy metals from wastewater streams using bio-waste [8]. A wide range of novel technologies, including the utilization of various plants for the biosorption of contaminants, are being developed for the treatment of contaminated water. Numerous investigations have been conducted to determine whether plants, either in their entirety or in specific parts, such as corn cobs, walnut shells, rice husk, or maize cobs, can remove harmful contaminants [9,10]. In recent years, biosorption has emerged as a promising approach for heavy metal remediation, with plant-based materials being widely explored as effective biosorbents [11,12]. This technique operates independently of metabolism and is eco-friendly and cost-effective. This review analyzes current knowledge on the use of plant-derived biosorbents, including agricultural by-products and other plant materials, for the biosorption of heavy metals. The review also highlights the mechanisms of biosorption, including ion exchange, complexation, precipitation, etc.

2. Methodology

This mini-review was designed to provide a focused, concise synthesis of current knowledge on plant-derived biosorbents for heavy metal removal. Unlike a systematic review, a mini-review emphasizes summarizing recent advances and key findings while maintaining breadth and clarity.

A structured literature search was carried out across major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, covering the period from 2017 to 2025. Keywords and Boolean combinations such as "*plant-derived biosorbents*," *"biosorption of heavy metals*," "*agro-waste adsorbents*," "*wastewater treatment*," and "*adsorption efficiency*" were used. The initial pool of studies was screened by titles and abstracts, followed by full-text evaluation.

Inclusion criteria were: (i) studies focusing on raw, modified, or activated plant-based biosorbents; (ii) experimental investigations reporting adsorption of heavy metals from aqueous solutions or real wastewater; and (iii) articles providing quantitative results such as adsorption capacity, percentage removal efficiency, or kinetic/isotherm modeling data. Exclusion criteria were: (i) non-English publications; (ii) reviews, book chapters, and conference abstracts without detailed experimental data; and (iii) studies lacking measurable adsorption parameters.

To strengthen coverage, references from key articles were also manually screened. This approach ensured a comprehensive yet concise evaluation of the efficiency of plant-derived biosorbents in wastewater treatment, while aligning with the scope of a mini-review.

3. Traditional Methods for Treating Heavy Metal Pollution

Several traditional methods are used for treating heavy metal pollution. Electro-flotation technology is used to treat minerals and wastewater. It effectively removes dissolved or suspended pollutants, including heavy metals and lubricants [13,14]. However, managing bubble evolution during the process is challenging. They often have low efficacy in removing pollutants. Electrocoagulation works by removing iron or aluminum ions from electrodes. The process generates *in situ* coagulants for efficient water treatment [15]. But electrocoagulation requires frequent replacement of sacrificial anodes. Chemical precipitation is the most common technique for removing metal ions [16]. It is effective at collecting inorganic metal ions from solutions. However, it generates more sludge during the process. This can lead to secondary contamination in the environment. The disposal of this additional sludge is costly. Additionally, these methods are sensitive to pH changes. Traditional methods are often inefficient, time-consuming, and require constant monitoring [17]. Many of these methods can be costly to implement. They do not always provide long-term solutions. Given these limitations of conventional techniques, researchers have increasingly explored biosorption as an alternative approach. Biosorption utilizes low-cost, eco-friendly biological materials, such as plant-derived wastes, to efficiently remove heavy metals, offering advantages including high selectivity, reusability, minimal sludge generation, and sustainability, making it a promising solution for wastewater treatment.

4. Biosorption

Biosorption is a process that selectively removes low concentrations of hazardous pollutants from aqueous solutions under various conditions [18,19]. This process has garnered significant attention across diverse scientific fields since the mid-20th century. Biosorption is a multimodal, physico-chemical, metabolism-independent, and passive technique that uses bio-waste to eliminate various water contaminants. The biosorption procedure entails two stages: a liquid or aqueous stage (a solvent, typically water) that conveys a dissolved species to be adsorbed (adsorbate, or metal), and a solid stage (adsorbent or biological substance) [13]. Complexation, electrostatic attraction, ion exchange, surface adsorption, diffusion, chelation, and microprecipitation are some biosorption mechanisms [20]. Biosorption operates independently of active metabolic functions and, unlike chemical methods, eliminates the need for sludge management. Therefore, biosorption efficiently reduces heavy metal concentrations while remaining environmentally friendly and cost-efficient [17]. The oxidation state, ionic radius, molecular weight, and concentration of heavy metals all affect biosorption [21]. Temperature, pH, and biosorbent dosage are the key parameters influencing biosorption. Among these, pH is the most significant factor, as it governs ionic dissociation, metal speciation, and binding sites in solution.

5. Biosorption by Plant-Derived Biosorbents

A wide range of plants and plant-based materials show strong potential for removing hazardous pollutants effectively [22]. This biosorption process works under a wide range of conditions and at low contaminant levels. It provides a simple and clean way to recover metals from diluted solutions. Biosorption requires low capital investment, as it utilizes affordable and renewable sorbents. These sorbents are derived from sources such as rice husk, orange peels, wheat husk, peanut shells, sawdust, and other plant parts or waste [23, 24]. Biosorption is beneficial when using stabilized biomass, as it allows biosorbents to be stored for long periods. There is no toxic effect caused by heavy metal presence or nutrient limitations in the process. It operates efficiently across a wide range of pH and temperature conditions. Moreover, chemical regeneration allows the adsorbent to be reused in multiple adsorption-desorption cycles, improving sustainability.

5.1. Fruits and vegetables.

Vegetable- and fruit-derived adsorbents are typically synthesized through simple steps, including collecting, washing, drying, grinding, activating, and sieving [25]. Agro-waste materials such as fruit peels and nut shells serve as sustainable adsorbents for pollutant removal [26] (Table 1). The major benefit of this approach is that it does not involve the use of hazardous chemicals and reagents.

A variety of techniques are employed to create vegetable and fruit-derived adsorbents, such as pyrolysis or carbonization of the material, chemical activation with an acid or base, deposition of natural material onto a substrate or other adsorbent material [27]. The selection of appropriate fruits and vegetables and their parts is crucial, with cost and availability being important factors. While some materials undergo basic or chemical processing, others are transformed into carbon. Orange peel powder (OP) was produced by simple processes such as washing, drying, and sieving. It was subsequently doped with iron (III) oxide-hydroxide (OPF) to enhance metal adsorption by metal oxides [28].

Hydrothermal treatment, carbonization, acid digestion, saponification, and surface impregnation are among the frequently used techniques for creating adsorbents derived from fruits and vegetables [25]. In the saponification process, alkalis hydrolyze cholesterol or fatty acids to produce the corresponding glycerol or fatty acid salts. For example, Mn^{2+} and Pb^{2+} were eliminated using saponified garlic peel [29] (Table 1).

Table 1. Modified plant-based biosorbents for heavy metal removal with target contaminants and key adsorption features.

Biosorbent	Target contaminants	Key features
Garlic Peel (Saponified)	Mn(II), Pb(II)	Improved kinetics and adsorption capacity over raw garlic peel.
Pomelo Peel +Fe(III)	As(V)	For efficient removal of As(V), anion exchange sites were created.
Potato Peel +Biochar	Cd(II),Ni(II)	Enhanced adsorption due to $MnFe_2O_4$ nanoparticles.
Pumpkin Husk +KOH	Cu(II)	Improved adsorption capacity with chemical modification.
Mangosteen Peel +CMP	Cr(VI)	Acid digestion increased adsorptive sites for heavy metal removal.
Citrus Peel +Aerogel	Heavy Metals	A stable super-molecular network formed for efficient adsorption.
Watermelon Rind	Zn(II)	Acid-digested adsorbent showed excellent removal efficiency.

5.2. Agricultural by-products as biosorbents.

Agricultural by-products are affordable and efficient biosorbents for eliminating heavy metals [30] (Table 2). These materials are rich in organic matter and functional groups capable of binding anions and cations. They are readily available, non-hazardous, and have no disposal concerns. Agricultural residues can be transformed into adsorbents, reducing disposal costs and offering a substitute for commercially available activated carbon [31]. Rice husk is a significant agricultural by-product with a high affinity for synthetic dyes and heavy metals. Rice husk activated with activated carbon has been shown to have high removal efficiency for several heavy metals from aqueous solutions [32]. Rice husk pretreated with tartaric acid and NaOH showed a biosorption effectiveness of 48.841 mg/g in removing Cu(II) ions from wastewater. Sugarcane bagasse, which contains 27% polyose, 23% lignin, and 50% cellulose, yields a rich adsorbent with a wide range of functional groups [33]. The biosorption efficiency of sugarcane bagasse treated with citric acid (pretreated with ethanol) was 122.4 mg/g. Sawdust from various origins has been assessed for its potential to carry out a biosorbent role. Mango tree sawdust treated with phosphate is a potential sorbent to eliminate Cr(VI) ions from electroplating process wastewater. The primary functional groups in its structure that aid in the adsorption of pollutants from wastewater are carboxyl, phenol, and amide. Activated carbon derived from peanut shells has been shown to remove a wide range of heavy metals. Activated peanut shells outperform several commercial adsorbents in the elimination of heavy metals. The biosorption capacity of Pb^{2+} by peanut shells was 39.0 mg/g [34]. Coir pith is an inexpensive adsorbent to remove Hg^{2+}, Ni^{2+}, and Cu^{2+} ions. Comparing the removal efficiency of $ZnCl_2$-treated coir pith to that of untreated coir pith, it was discovered that the former had a relatively high removal efficiency.

Table 2. Adsorption efficiencies of various agro-waste biosorbents for heavy metal removal.

Biosorbent	Target heavy metals	Adsorption efficiency (%)	References
Coconut waste	Pb^{2+}, Cd^{2+}	Upto ~ 93% , 88.7 – 98.2%	[10]
Lemon peel	Ni^{2+}, Cd^{2+}	> 90 %	[35]
Mulberry leaves	Pb^{2+}, Cu^{2+} and Zn^{2+}	69%, 85% and 100%	[36]
Banana peel	Cu^{2+}, Pb^{2+}	69.3%, 93.4%	[37]
Green tea waste	Cu^{2+}, Cr^{6+}	99 – 100 %	[38]
Elderberry, Gooseberry, and Paprika residues were activated using acetic acid	Cu^{2+}, Cd^{2+} and Fe^{3+}	~99.5%	[39]
Shell dust and chitosan	Cu^{2+}, Cd^{2+} and Pb^{2+}	Upto ~ 95%	[40]
Groundnut husk	Cu^{2+}	Upto ~ 91%	[41]
Peanut shells	Cu^{2+}	~ 90 – 95 %	[42]
Corn cob	Ni^{2+}, Pb^{2+}	~75% , ~98%	[24]

5.3. Other plant-based biosorbents.

The fruit peel of *Artocarpus nobilis* is proven to be an effective low-cost biosorbent for Ni^{2+} [43]. Pb and Cd were biosorbed from aqueous solutions using curry leaf powder (CLP), a promising green, environmentally friendly biosorbent. The rough surface of CLP exhibited a monolayer sorption capacity of 60.17 and 37.03 mg g−1 for Pb and Cd, respectively, at varying starting concentrations between 50 and 200 mg/L [44]. Phytolacca acinosa-derived biochar was investigated to assess the mitigation of heavy metals, specifically Pb, Cu, Ag, and Cd [45]. The stalks of rice plants (*Oryza sativa L*.), reeds (*Phragmites Trin.)*, and cassava (*Manihot esculenta Crantz*) were utilized to extract Cd, Cr, Cu, Ni, Pb, and Zn from wastewater [46]. The biosorption of Cu and Pb ions from wastewater was accomplished using Gingko leaves, peanut shells, and Metasequoia leaves [47]. Straws of sunflower, maize, and wheat, sunflower straw husk, orange shell, and chestnut shell were found to be effective in the removal of Pb^{2+} from wastewater [48]. Similarly, rice straw was found to be effective in removing Cu2+ and Zn2+ ions [49] (Table 3).

Table 3. Adsorption capacities and operational parameters of various plant-derived biosorbents for heavy metal removal.

Biosorbent (plant source)	Target metal	Q_{max} (mgg^{-1})	Adsorbent dose (g/L)	Optimum pH	Contact time	Kinetics and isotherm model	References
Mango seed (raw)	Pb^{2+} Cd^{2+}	263.4 (single study)	–	5.0 7.5	10 min	Pseudo – 2nd order; Redlich - Peterson	[50]
Banana peel (raw)	Pb^{2+}	66.7	0.1 – 1	5.5	30 – 60 min	Pseudo – 2nd order; Langmuir	[37]
Rice husk	Cu^{2+}	2.30	1 – 128	6 – 7	60 min	Pseudo – 2nd order; Langmuir	[51]
Orange peel (Activated carbon)	As^{5+}	10.91	3.3	4.2	4.8 h (288 min)	Pseudo – 2nd order; Freundlich	[52]

Biosorbent (plant source)	Target metal	Q max (mgg-1)	Adsorbent dose (g/L)	Optimum pH	Contact time	Kinetics and isotherm model	References
Lupinus albus seed hull (seed hull powder)	Pb^{2+}	357.14	0.4	5.5	60 min	Pseudo – 2nd order; Langmuir	[53]
Onion peel (raw)	Co^{2+}	58.46	1	7.0	120 min	Pseudo – 2nd order; Langmuir	[54]
Coconut husk biochar	Pb^{2+}	56.53	0.5	6	60 min	Pseudo – 2nd order; Temkin	[55]
Hydro-pyrochar from corn cob doped with Mg (HCC-Mg)	Pb^{2+}	87.08	1	5	120 min	Pseudo – 2nd order; Sips	[56]
Peanut shell activated carbon	Pb^{2+}	130.89	2	4.5	60 min	Pseudo – 1st order; Langmuir	[57]
Carbonized pomegranate husk (CPH) (pyrolyzed at 400 °C)	Cd^{2+}	92.75	_	8	40 min	Pseudo – 2nd order; Freundlich	[58]

6. Biosorption Mechanism

Biosorption is a passive technique that uses bio-waste to eliminate water contaminants. It involves two stages: a liquid or aqueous stage (water) and a solid stage (adsorbent or biological substance) [59]. The adsorbent's high affinity for the adsorbate confers selective binding via various mechanisms, leading to changes in the adsorbate distribution pattern or concentration [60]. Biosorption mechanisms include complexation, electrostatic interactions, ion exchange, surface adsorption, diffusion, chelation, and microprecipitation [20]. Adsorption is linked to the adsorbent's surface area; a larger surface area provides more adsorption sites, increasing efficacy. Physiosorption is driven by weaker forces, such as van der Waals, while stronger chemical bonds form in chemisorption. The adsorbent surface plays a crucial role in determining the strength of these interactions. In complex systems or specific conditions, both physisorption and chemisorption can occur simultaneously [61]. This dual interaction enhances the overall biosorption capacity. In physical adsorption, metal ions adhere to the surface of inactive biomass primarily through weak Van der Waals forces, rather than forming chemical bonds, making the process largely reversible [62]. Covalent bonding, Van der Waals forces, biomineralization, electrostatic interactions, and redox reactions all affect physical adsorption. pH of the sorption medium beneath the metal ion has a major impact on its ability to adsorb. Alkaline conditions have been shown to promote the adsorption of metal cations to cell surfaces by dislodging negatively charged functional groups. Physical adsorption was only possible under alkaline conditions, with the biomass's carboxyl and hydroxyl groups contributing to lead biosorption by Hami melon peels [63].

The efficacy of biosorbents in removing contaminants from water systems is significantly influenced by the presence of diverse functional groups [64] (Figure 1). The behavior of these groups can be influenced by the medium's pH or the water's acidity or alkalinity. Lowering the pH can cause functional groups on a biosorbent's surface to protonate, resulting in a positive charge. It can also limit or prohibit their sorption. Raising the pH reduces electrostatic repulsion, resulting in increased biosorption via electrostatic attraction between the biosorbent and contaminants. Acidic environments create positively charged metal ions, which are highly attracted to negatively charged biomass. This interaction facilitates effective biosorption in low pH conditions. Conversely, at higher pH levels, metal ions tend to bind with hydroxyl ions. It further leads to the formation of insoluble precipitates. This precipitation reduces the availability of free metal ions, diminishing their affinity for biomass. As a result, the biosorption process becomes less effective in alkaline environments.

Ion exchange is the principal procedure underpinning biosorption, using chemical groups on the biosorbent surface [64]. It is a reversible process in which anions on the biosorbent surface are attracted to and may interact with metal cations in solution [65]. Carboxyl, hydroxyl, and phenol groups promote this process, releasing two H^+ or Na^+ ions into the solution. The process is impacted by the pH of the solution. In acidic environments, excess H+ ions may compete with positively charged contaminants for sorption sites on the biosorbent. Under basic conditions, OH- ions become more prevalent and can compete with negatively charged contaminants for sorption sites [66]. Complexation is a chemical process in biosorption where metal ions form complexes with ligands that have two unshared electrons. Functional groups on the biosorbent act as ligands, enabling heavy metal ions to form coordinate bonds. Chelation is a specialized type of complexation that occurs when a ligand forms multiple bonds with a single metal ion. This results in a stable, encircling structure around the metal ion. Chelation enhances the stability and efficiency of the biosorption process [67] (Table 4).

Table 4. Biosorption mechanisms of plant-based biosorbents for heavy metal removal.

Mechanism	Key functional groups/process	Typical conditions	Plant-based biosorbent → target metal(s)	Evidence reported	References
Ion exchange (cation exchange)	Exchange of metal ions with cations (e.g., calcium, potassium) bound to carboxyl and hydroxyl groups	Neutral to mildly alkaline pH; presence of exchangeable cations	Acid-group-modified biochar derived from peanut shells → Lead (Pb^{2+})	Ion exchange suggested by functional-group shifts in Fourier-transform infrared spectroscopy and the presence of acidic groups facilitating binding	[68]
Surface complexation/ chelation	Coordination of metal ions via oxygen/nitrogen donors—carboxyl, hydroxyl, carbonyl, phenolic groups	Generally effective across moderate pH, enhanced at higher pH	Biochar derived from urban pruning waste → (Pb^{2+}), (Cd^{2+}), (Mn^{2+})	Spectroscopy and adsorption modeling are consistent with inner-sphere complex formation	[69]
Electrostatic attraction	Coulombic attraction between the charged biosorbent surface and oppositely charged ions	For anionic metals: acidic pH (surface protonated); for cationic metals: alkaline pH (surface deprotonated)	Orange peel (raw and chemically modified) → Chromium (VI) species ($HCrO_4^-$, $Cr_2O_7^{2-}$)	Point of zero charge analysis and pH-dependent uptake showed maximum sorption at low pH due to protonated sites	[70]
Reductive adsorption (reduction + binding)	Surface-associated reducing agents (such as Fe^{2+} species or electron-donating groups) reduce toxic metals to less toxic forms, which then bind or precipitate	Acidic to mildly acidic solutions	Iron-modified rice straw biochar → Chromium (VI)	X-ray photoelectron spectroscopy showed the disappearance of Cr(VI) peaks and emergence of Cr(III); Fourier-transform infrared and X-ray diffraction confirmed reduced chromium binding	[71]
Surface precipitation	Formation of insoluble metal carbonates/hydroxides on biochar surfaces rich in mineral ash	Near-neutral pH; high ash or carbonate content	High-ash, highly porous Lv700-63 biochar →(Pb^{2+}), (Cd^{2+}),(Mn^{2+})	Electron microscopy, energy-dispersive spectroscopy, and reduced potassium signal indicate metal-carbonate precipitation	[69]
π-Electron/Phenolic Coordination(often	Interaction of metal ions with delocalized π-electrons in aromatic rings and phenolic hydroxyls	Enhanced with increasing pyrolysis temperature due to greater aromaticity	Urban pruning waste biochar (higher pyrolysis) → (Pb^{2+}),(Cd^{2+}),(Mn^{2+})	Fourier-transform infrared shifts in aromatic and carbon-oxygen bands; π-electron involvement stated	[69]

Mechanism	Key functional groups/process	Typical conditions	Plant-based biosorbent → target metal(s)	Evidence reported	References
alongside complexation)					
Composite-assisted (layered double hydroxides/mineral coupling)	Co-precipitation or ion exchange on in situ mineral phases (e.g., iron/manganese hydroxides) embedded in biochar	Depends on the type of mineral modifier; effective across varied pH	Iron-modified biochars (e.g., Fe- → (Cd^{2+}), (Pb^{2+}) in soils	Enhanced pH and multiple adsorption pathways, including precipitation and complexation	[72]
Multifactor (ion exchange, electrostatic, complexation, precipitation)	Combined mechanisms, including physical adsorption, ion exchange, surface complexation, electrostatic attraction, and precipitation on the modified biochar surface	Broad pH; modification with calcium/iron enhances multiple mechanisms	Calcium–iron modified biochar →(As), (Cd),(Pb)	Schematic model and evidence for multiple simultaneous adsorption pathways	[73]
Magnetic biochar surface complexation and reduction	Adsorption via surface functional groups (hydroxyl, carboxyl, amine) coupled with the reduction of Pb(II) to elemental lead (Pb^0)	Often variable pH; iron presence enables reduction reactions	Magnetic biochar → Lead (Pb^{2+}) removal	Surface complexation and reduction mechanisms inferred; elemental lead generation proposed	[74]

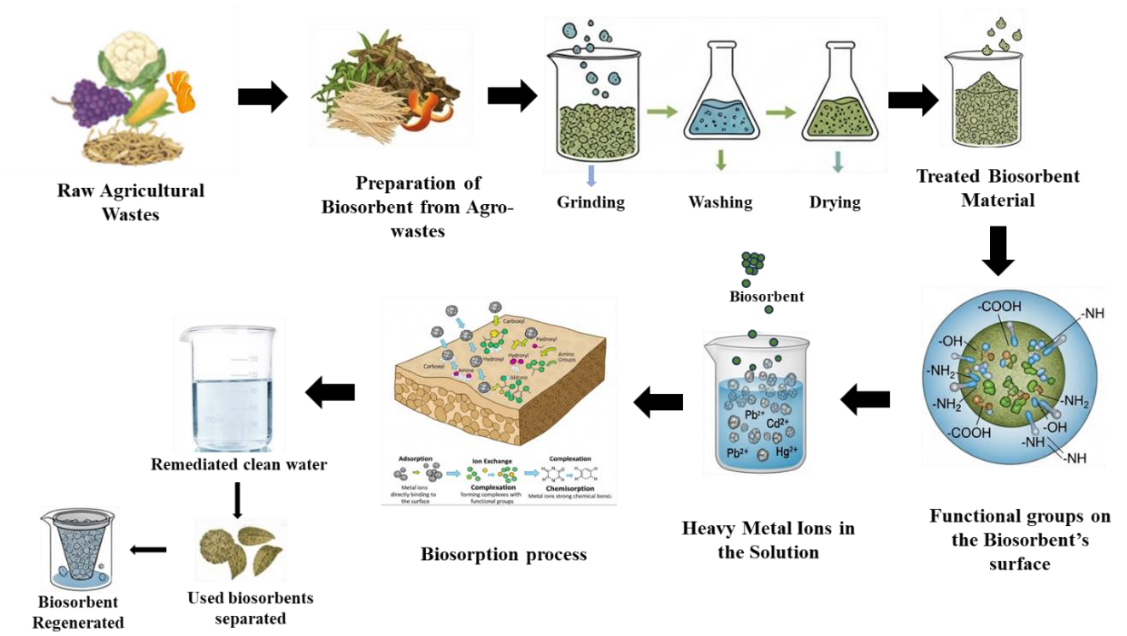

Figure 1. Mechanism of heavy metal removal by plant–based biosorbents.

7. Advantages and Drawbacks of Plant-Based Adsorbents

Biosorption using plant-derived adsorbents has proven effective for the removal of toxic metal ions from aqueous solutions. These materials are used to create wastewater treatment technologies that are inexpensive, effective, clean, and environmentally friendly. Forest waste and agricultural byproducts are examples of plant-based materials that have a high affinity for removing heavy metal ions.

The advantages of plant-based adsorbents in biosorption of metals are the following: Plant materials are typically agricultural waste or abundant natural resources, making them economically viable; Being natural and biodegradable, they do not create additional environmental problems; Natural functional groups in plants (like cellulose and lignin) provide excellent metal binding capacity; Adsorbents can be recycled for the removal of heavy metals after desorption.

They can be applied to a variety of toxic-metal detoxification processes for wastewater and drinking water. By modifying and improving plant materials, adsorbents can be transformed into commercial adsorbents. They are efficient at eliminating metal traces in aqueous environments [75].

The drawbacks of plant-based adsorbents in the removal of heavy metals are listed as follows: Natural variation in plant materials can lead to unpredictable results in metal removal. Certain adsorbents work best with specific metal ions and are ineffective with others; often requires chemical or physical modification to enhance binding capacity. Prior to application, the adsorbent must undergo pre-washing and pretreatment. Certain materials are inefficient in their natural state. Treatment costs may rise as a result of this chemical alteration; Plant materials can deteriorate during storage, affecting their long-term effectiveness [75].

These factors influence the practical application of plant-based biosorbents in heavy metal removal processes

8. Conclusion

Biosorption using plant-derived biosorbents offers a sustainable, low-cost alternative to conventional treatment methods for removing heavy metals from wastewater. This method utilizes plant-based materials and agricultural byproducts, such as maize cobs, orange peels, groundnut shells, coir pith, jute fiber, and rice husks, which remove heavy metals through ion exchange, complexation, and precipitation. Their porous structure and abundant surface sites enhance adsorption efficiency, making them suitable for a wide range of applications. The eco-friendly and cost-effective nature of biosorption, along with its potential to be converted into biofertilizers that enhance crop growth and soil health, makes it a promising alternative to chemical-intensive practices. Despite promising laboratory results, critical gaps remain in limited studies of real wastewater systems, regeneration efficiency, biosorbent stability, and performance under multi-metal or complex matrices. Addressing these issues requires further research on scale-up processes, improving selectivity through surface modification, and enhancing regeneration and reuse cycles. Future research should focus on standardizing adsorbent preparation methods to ensure reproducibility, developing eco-friendly and cost-effective pretreatment strategies, and exploring stabilization techniques to improve storage and shelf life. Integrating biosorption with complementary technologies such as membrane filtration, advanced oxidation, or constructed wetlands could improve overall treatment efficiency. In addition, policy interventions are essential to encourage agro-waste valorization, establish biosorbent quality standards, and promote adoption in wastewater management frameworks. By bridging scientific innovation with supportive policies and hybrid treatment approaches, biosorption can transition from a promising laboratory technique to a practical, scalable solution for sustainable water treatment and environmental protection.

Author Contributions

Conceptualization, S.P.; writing—original draft preparation, S.P.; validation, L.B.S.; writing—review and editing, L.B.S., D.P.K.S., and A.P.D.; supervision, L.B.S. and A.P.D. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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