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Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 1, March 2026 issue

Environmental Remediation and Sustainable Approaches to Heavy Metal Removal: A Comprehensive Review of Biosorption Techniques

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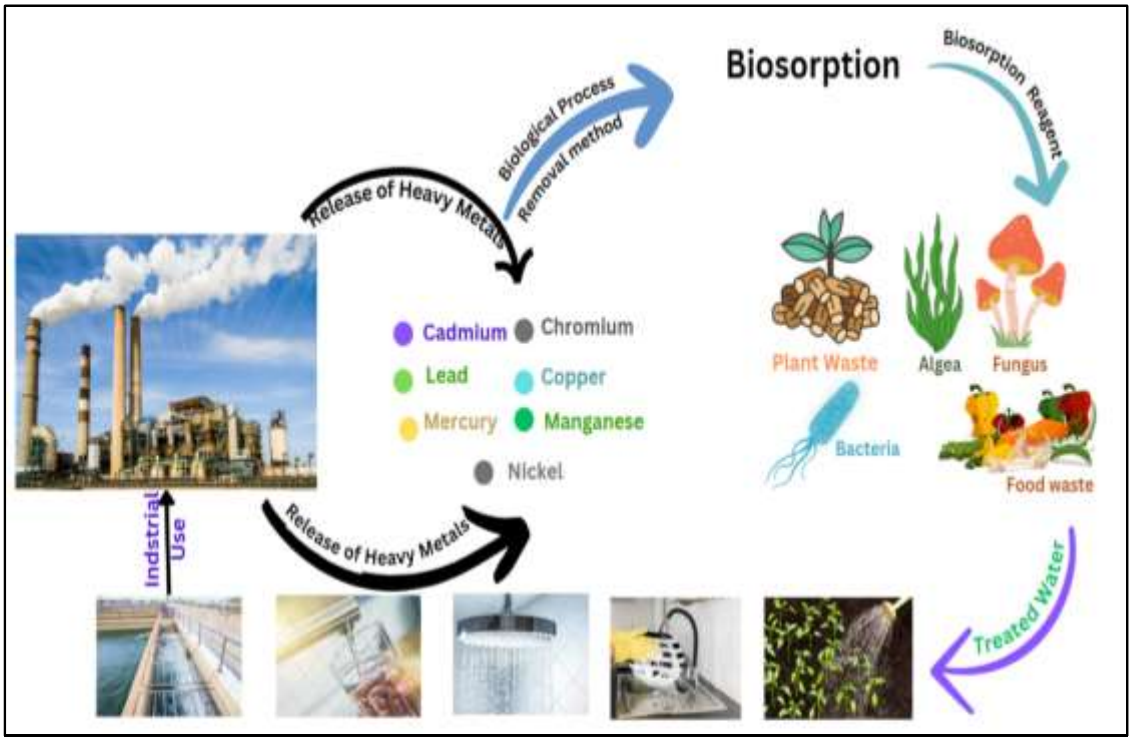
Key Words	Biosorption, Heavy metals, Wastewater, Pollution removal, Low-cost adsorbents
DOI	https://doi.org/10.46488/NEPT.2026.v25i01.B4334 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Magdum, P. and Itankar, N., 2026. Environmental remediation and sustainable approaches to heavy metal removal: A comprehensive review of biosorption techniques. *Nature Environment and Pollution Technology*, 25(1), p. B4334. https://doi.org/10.46488/NEPT.2026.v25i01.B4334

Graphical abstract



ABSTRACT

Heavy metal-laden contaminated water poses a severe environmental threat due to its bioaccumulation tendency, persistent nature, and toxicity. Conventional wastewater treatment techniques, such as ion exchange, chemical precipitation, membrane separation, and electrocoagulation, can result in secondary pollutants, require high energy use, and involve high costs. This review discusses environmentally friendly methodologies for the removal of heavy metals from aqueous streams, and the biosorption process is a viable alternative to address sustainability concerns in conventional, energy-intensive industrial processes. The biosorption process utilizes a wide range of natural biomasses, such as plants, fungi, algae, and bacteria, for the sequestration and removal of heavy metals from aqueous solutions. Biosorption is mediated through various mechanisms, including physical adsorption, ion exchange, complexation, precipitation, and intracellular transport. The effectiveness of a biosorbent is based on the efficiency of sequestration and removal of heavy metals under given conditions. Some important factors affecting this include pH, temperature, contact time, biomass loading, and initial heavy metal ion concentration in the solution. Additionally, the capacity for biosorption for regeneration and reuse increases its commercial viability. This work explored the sources of biosorbents and the driving forces that govern their biosorption efficiency. Furthermore, this study provides an in-depth discussion of the factors that affect the effectiveness of the process. It establishes a fundamental understanding of biosorption mechanisms and influencing factors, paving the way for future commercialization of this promising technology.

Introduction

Environmental pollution due to heavy metals has multiplied from a regional problem to a worldwide one, exacerbated by rising urbanization, industrialization, and poor wastewater treatment. Water pollution, which may arise from an array of things like agriculture, wastewater, oil spills, and radioactive materials, is among the significant problems civilization is currently experiencing (Jahan & Singh, 2023). Heavy metals (HMs) such as arsenic, copper, cadmium, chromium, lead, nickel, and zinc are persistent pollutants that accumulate in the environment, and industrial effluent in particular has the potential to be a substantial carrier of these pollutants. (Aliyu Haruna Sani, Amanabo Musa And Musa Dickson Achimugu, 2023). Because they contaminate the habitats of marine organisms, these heavy metals constitute a serious hazard to water bodies, including streams, lakes, and oceans. (Jahan & Singh, 2023). HMs bioaccumulate in the food chain, people inadvertently endanger their health when they consume contaminated foods like fish and vegetables. Owing to the threat, regulatory bodies worldwide have tightened permissible discharge limits and call for sustainable remediation alternatives.

Biosorption, as a biologically inspired technique, has garnered attention due to diverse biosorbents, ranging from microbial biomass to plant-based waste. However, in terms of data comparability, method standardization, and clarity about sorption mechanisms across various biosorbent kinds, the area is still fragmented despite a large number of investigations. To create systems that are adaptable, dependable, and economical for treating waters, more research and development of bioprocesses is necessary. Presenting the state of the art in biosorption research and contrasting findings from previous studies are the goals of this work.

The originality of this work lies in three main aspects:

Material Innovation: Modification (chemical/physical) enhances surface area and functional groups, thereby increasing metal-binding affinity. Modified selected biosorbents with their adsorption capacity are elaborated in the review.

Critical Analysis of Influencing Parameters: To assess how important aspects like pH, temperature, contact time, biomass dosage, and initial metal ion concentration affect biosorption performance. This work focuses on results from diverse investigations rather than presenting experimental data. Based on kinetic and isotherm models from the literature, the review also addresses the mechanisms at play, including complexation, ion exchange, physical adsorption, and others.

Sustainability Emphasis: The use of abundant, biodegradable biomass supports circular economy principles and promotes waste materials for environmental remediation.

Overall, the findings contribute to expanding the library of efficient biosorbents and offer a pathway for practical, sustainable heavy metal remediation technologies in developing regions.

2. Biosorption Insight

Plants and microorganisms produce many biomaterials in the form of biomass, which is utilized in the biological physicochemical process of biosorption to absorb or adsorb a target species, such as metal ions or dyes. (Gadd, 2009).

Biosorption using biomaterial is a two-phase process: one for the mobile or liquid phase and one for stationary, which in this case was biomass. The mobile phase is usually an aqueous solution of dissolved metal ions/dyes known as sorbates. Algae, bacteria, fungi, and plants act as immobile or stationary phases of biosorbents in treatment processes. They act as effective biomass for removing heavy metals from aquatic systems (Apriani et al., 2024). Metal ions get adsorbed mainly through the cell walls of these biological sorbents (Ali Redha, 2020). A variety of different biosorbents like Fungi and Algae consist of an extensive number of functional groups in their cell walls, which play an important role in the process of biosorption.

These functional groups include carboxyl (-COOH) groups found in proteins, fatty acids, and organic acids; esters (-O-) present in lipids; carbonyl groups (C=O), which can be either internal or terminal, as seen in ketones and polysaccharides; phosphate groups; ester linkages (RCOOR') found in lipids and in alcohols and carbohydrates, hydroxyl (-OH) groups are present (Silva et al., 2018). Certain biosorbents possess functional groups, such as imidazole, amino, sulfonyl, sulphate, phenolic, thioether, and amide groups, which improve the adsorption procedure. Calculation using Equation 1 is carried out to find the percentage removal of metal during the biosorption process

$$\%Removal\ of\ Cr(VI) = \frac{C_{initial} - C_{final}}{C_{initial}}\ x\ 10 \qquad \text{Eq. No. 1}$$

The biosorption capacity and equilibrium time of the adsorption process were calculated using the following formulas:

$$Q = \frac{(C_o\text{-}C_e)\ V}{m}$$ Eq. No. 2

Where

-C_f: Final concentration of Cr(VI) in solution (mg/L)
-Ci: Initial concentration of Cr(VI) in solution (mg/L)
-C_0: Initial concentration of Cr(VI) in solution (mg/L)
-Ce: Concentration of Cr(VI) in solution at equilibrium (mg/L)
-V: Volume of the solution (L)
-m: Mass of biomass (g)
-Q: Metal uptake or adsorption capacity (mg/g)
(Singh, Itankar and Patil, 2021).
The quantity of heavy metal ions that a biosorbent can adsorb or absorb (biosorbents) is directly proportional to its sorption capability (Zyoud *et al.*, 2019).

3. Mechanisms of biosorption

The ability of biological materials to accumulate heavy metals from wastewater through either spontaneous or metabolically mediated uptake pathways (using ATP) is known as biosorption and bioaccumulation, respectively (Ahmed *et al.,* 2022; Chugh *et al.*, 2022).The biosorption mechanism is also influenced by nature and number of binding/reactive sites, accessibility and availability of binding sites, and affinity between the binding site of the biosorbent and the concerned metal ion are just a few of the properties that affect the mechanism of biosorption (Abdel -Aty *et al.*, 2013). It can also occur as a result of certain types of inactive, non-living microbial biomass that can bind and concentrate heavy metals even from very dilute aqueous solutions.
Biosorption mechanism includes ion exchange, physical adsorption, chemical adsorption, precipitation, complexation, and electrostatic interactions. (Javanbakht, Alavi and Zilouei, 2014; Ismail and Moustafa, 2016; Nadeem *et al.*, 2016). In certain situations, many mechanisms may occur together in a multistage procedure (Noli et al., 2019). Biosorption efficiency and specificity depend on the type of biosorbent used and the physicochemical characteristics of the pollutants. Furthermore, because of the biological complexity of biosorbents, the majority of these processes are not completely known in detail.

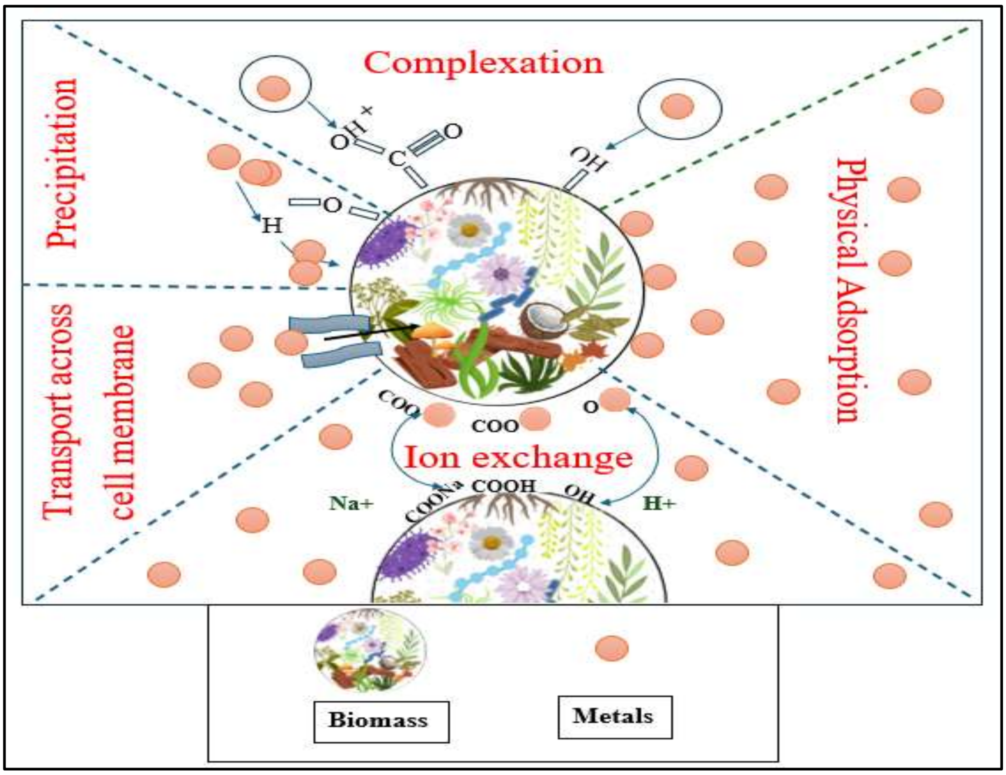


Fig. 1. Mechanism of biosorption

Biosorption can be (i) metabolism-dependent or (ii) non-metabolism-dependent according to biomass activity. The non-metabolic mechanism is depicted in Figure 1, which covers the mechanisms involved, such as intracellular accumulation, precipitation, ion exchange, and cell-surface adsorption/precipitation (Manmohan & Gajalakshmi, 2024).

Precipitation and passage across the cell membrane are mechanisms of biosorption or bioaccumulation that are dependent on cell metabolism, whereas physical adsorption, ion exchange, precipitation, and complexity are mechanisms of biosorption that are independent of cell metabolism (Avanzi *et al.*, 2014; Rene *et al.*, 2017). Regarding the second criterion, transport across the cell membrane results in extracellular accumulation and precipitation, while ion exchange, complexation, physical adsorption, and precipitation result in cell surface sorption and precipitation. Precipitation, on the other hand, results in intracellular accumulation (Ali Redha, 2020). Another fundamental mechanism observed in the majority of biosorption types is simple diffusion. The coordination, stereochemical, and chemical properties of the target metal, which comprise the ionic radii, ion mass, and oxidation state of the metal ion, as well as other variables, may play a role in regulating these processes (Kanamarlapudi, Chintalpudi, and Muddada, 2018).

Other parameters, such as concentration, time, pH, temperature, and the complex matrix of the solution containing the metal ion, depend on the operational conditions in which biosorption occurs. (Kanamarlapudi, Chintalpudi and Muddada, 2018).

3.1. Physical adsorption

Physical adsorption is one of the major biosorption processes, in which adsorbates adsorb onto biosorbent surfaces by weak interactions such as van der Waals forces, dipole-dipole interaction, London dispersion forces, and hydrogen bonding. Such forces tend to interact with functional groups on the biosorbent surface, such as those found on cell walls. Physical adsorption can lead to the development of several layers of adsorbates on the biosorbent. Several factors impact the efficiency of physical adsorption, including biosorbent surface area, temperature, pressure, pore structure, nature of the adsorbate and adsorbent, and, in some instances, solution pH (Bashir et al., 2019). Research on Pb biosorption using hami melon peels revealed that physical adsorption was highest in alkaline media. This resulted from the engagement of hydroxyl (-OH) and carboxyl (-COOH) groups on the surface of the biomass, which enhanced metal binding (Bashir et al., 2019). Similarly, pinewood biomass-derived biochars through hydrothermal liquefaction have been used to remove Pb from water, affirming physical adsorption's efficiency in metal recovery processes. These results confirm the relevance of surface functional groups as well as environmental parameters to guarantee optimal physical adsorption to treat wastewater."

3.2. Ion exchange

Ion exchange is an immobile solid material-bound, stoichiometric, and reversible chemical process whereby ions of an electrolyte solution or molten salt are exchanged with ions of like charge bound to an immobile, solid material, to achieve overall electroneutrality. (Gadd, 2009). The most widely used ion-exchange materials are synthetic

Organic resins, inorganic matrices, and advanced hybrid materials are the most widely used synthetic ion-exchange materials.

For instance, *Ganoderma lucidum* fungus has been found to biosorb copper ions through ion exchange, as enabled by polysaccharide-rich cell walls of microorganisms such as bacteria and fungi, which allow counter-ion exchange (Ali Redha, 2020).

Studies have proven that heavy metal ions like cadmium(II), copper(II), and zinc(II) are bound to brown algae, with release of lighter ions such as sodium, potassium, magnesium, and calcium (Abdi & Kazemi, 2015; Volesky & Holan, 1995). Similarly, rice straw, which is a non-metabolism-dependent biosorbent, removes cadmium (II) ions effectively by ion exchange of lighter ions. Solution pH plays an extremely crucial role in ion-exchange mechanisms. For instance, ion exchange is responsible for lead ion biosorption by hami melon peels at pH levels that are relatively low, while electrostatic interaction is responsible at pH levels that are relatively high.

Between lead ions and such functional groups as hydroxylate and carboxylate on biomass becomes increasingly prevalent (Bashir et al., 2019).

Furthermore, cyanobacteria like *Spirulina* were able to biosorb copper(II), chromium(III), and cadmium(II) ions by means of ion exchange, facilitated by functional groups like carboxyl, phosphate, and hydroxyl groups on their surface (Kanamarlapudi et al., 2018). Such findings exhibit the diversity of ion exchange in biosorption processes in different biosorbents and environmental circumstances.

3.3. Complexation

Complexation is the process of electrostatic attraction or covalent bonding of metal ions and organic molecules that serve as ligands capable of donating electrons (Weng et al., 2022). Chelation is an advanced form of complexation where an organic ligand forms covalent bonding with the metal ion from multiple directions and results in more stable resultant complex. Hard and Soft Acids and Bases (HSAB) theory predicts that elements be classified as hard or soft bases (mainly non-metals) and as hard or soft acids (mainly metals) is the premise upon which metal ions and organic ligands' affinity depends, is the most crucial parameter in complexation. For being of soft acidic type, lead selectively covalent binds to biosorbent organic ligands that bear soft base like nitrogen or sulphur. Moreover, borderline-classified ions like manganese, zinc, cadmium, as well as copper, also possess high affinity to form compound's complex with organic compounds that bear nitrogen or sulphur (Afolabi & Musonge, 2025). But availability and accessibility of that binding site that contains base's donor atom matter to influence complexation. One can confirm that biosorption mechanism is done by complexation or not by performing desorption experiments using energy dispersive X-ray analysis (EDX), transmission electron microscopy (TEM), and scanning electron microscopy (SEM) (Bhat et al., 2024).

Wastewater can be treated effectively using complexation to strip metal ions like Pb, Cu, Zn, and Cr. In undertaking this, it is important to take into consideration parameters like ligands, cost, toxicity, and possible environmental implications (Chai, et al., 2021).

3.4. Precipitation

One of the metabolism-dependent processes in biosorption is precipitation, which is the formation of insoluble forms of metals as precipitates; however, precipitation can also lead to metabolism-independent biosorption. Precipitation results from the active defence process of microorganisms in metabolism-dependent biosorption upon exposure to toxic metal ions (Ali Redha, 2020). Precipitation is triggered by chemical interaction of metal ions with the functional groups of the cell wall of the biosorbent in metabolism-independent biosorption (Kanamarlapudi, Chintalpudi and Muddada, 2018). Such processes might involve oxidation-reduction reactions.

3.5. Transport across the cell membrane

Microorganisms are the only organisms that often exhibit the mechanism of heavy metal ion transport across cell membranes (Patil et al., 2024; Shafiq & Rehman,2024). This mechanism consists of two stages, the first is called independent binding metabolism and involves the binding of metal ions to binding sites on the microorganism's cell wall (Spain et al., 2021). The second stage is metabolism-dependent intracellular uptake and involves the transport of metal ions into the cell through the cell membrane (Ali Redha, 2020). This technique is analogous to how necessary metal ions are absorbed by cells. Heavy metal ions with charges and ionic radii comparable to those of essential metal ions have been reported to deceive cellular metal transport mechanisms.

4. Types of Biosorbents

4.1 Bacteria

Gram-positive and gram-negative bacteria are categorized according to cell wall thickness and composition, which is the primary distinction between the two types of bacteria(Zyoud *et al.*, 2019). Thicker peptidoglycan layers linked by amino acid bridges were observed on the cell walls of gram-positive bacteria. Gram-positive bacteria contain polyalcohols by name, teichoic and teichuronic acids, which are connected by phosphodiester bonds and adhere to the peptidoglycan of the cell wall; therefore, they have a greater capacity to eliminate heavy metal cations because of their substantial electronegative charge density (Tsezos, Remoundaki and Hatzikioseyian, no date; Abdi and Kazemi, 2015)

Heavy metal biosorption by bacteria is commonly facilitated by functional groups, including oxygen, nitrogen, sulphur, or phosphorus. Using FTIR spectrum data, a finding on the biosorption of lead(II) ions by Aeromonas hydrophila revealed that the hydroxyl, sulphate, thiol, thioether, phosphate, phosphonate, carboxyl, and amine groups of the biosorbent surface exhibit higher removal capacity of lead(II) ions from aqueous medium. In a fairly recent study, the removal of Uranium (VI) biosorption onto Bacillus amyloliquefaciens was investigated. FTIR and XPS of Bacillus amyloliquefaciens suggest the presence of functional groups like -COOH, -OH, and -NH_2 (Liu *et al.*, 2019).

4.2 Algae

Micro-algae and macro-algae are two main phyla of algae. Macro-algae are multicellular marine algae (macroscopic) that can grow in saltwater and freshwaters (Pinto et al., 2023). Macro-algae can be differentiated into three divisions based on pigmentation: Chlorophyta (green macroalgae), Rhodophyta (red macroalgae), and Phaeophyta/Ochrophyta (brown macroalgae) (Handayani et al., 2023).

Micro-algae, on the other hand, are photosynthetic one-celled plants that can grow in surface water (Goswami et al., 2022). Micro-algae can be distinguished based on their morphology, color, and orientation of photosynthetic membranes (Fernández et al., 2018). Blue-green algae (cyanobacteria), green algae, diatoms, and golden algae further classify the microalgae (Rajkumar & Yaakob, 2013).

Algae hold high biosorption capacity thanks to cell wall structure that is made up of chitin, polysaccharides, proteins, and lipids (Ahmed et al., 2022). All these components have important functional groups that support biosorption. Algae contain oxygen, nitrogen, phosphorus, and sulphur as the major functional groups that support heavy metal adsorption on the algae surface.

When comparing different macroalgae, it was observed that brown algae exhibited high metal binding. Cellulose, alginic acid, polymers(such as mannuronic and guluronic acids) complexed with light metals (such as calcium, potassium, and sodium), and polysaccharides (such as fucoidan) make up the majority of cell walls. Fucoidan and alginate both can bind metals by ion exchange; alginate's primary binding sites for biosorption are carboxyl groups, followed by sulphate groups (Hamza *et al.*, 2022). Proteins, which comprise functional groups such as amino, carboxyl, hydroxyl, and sulphate that aid in metal biosorption, constitute the majority of the material in the cell walls of green algae. However, despite having mostly cellulose in their cell walls, red algae can biosorb substances because they contain sulphated polysaccharides derived from galactans. The cell wall composition of microalgae varies slightly from that of other algae because they are primarily composed of polysaccharides, lipids, and proteins. These substances include carboxyl, hydroxyl, phosphate, and sulphate groups that give the surface of algae an overall negative net charge, which facilitates the biosorption of metal cations by counter-ion interactions.

Of all the different types of algae and biosorbents, brown algae have shown the highest capacity for biosorption of various metal ions. It's surface area to volume ratio is large.It's readily available, produces little sludge. Furthermore, biosorbed metals may be recovered and regenerated by brown algae. All things considered, algae are the most extensively used biosorbents due to their accessibility, comparatively low processing costs, and exceptional efficiency.

It was studied that the Blue-green algae, Spherical Anabaena, were efficient at extracting Pb (II) and Cd (II) from aqueous solutions (Ali Redha, 2020). The results show that the algae can remove lead (II) and cadmium (II) with relatively high biosorption capacities, with estimated levels of 111.1 mg/g and 121.95 mg/g, respectively (Abdel-Aty et al., 2013). The FTIR analysis of functional groups on algal surfaces indicates that amino, carboxyl, hydroxyl, and carbonyl groups bio-sequester metal ions (Abdel-Aty et al., 2013).

4.3 Fungi

Fungi possess a unique high cell wall composition, which in turn shows the existence of a variety of functional groups that may affect the elimination of metals. Mannoproteins (glycoproteins), β-Glucans(polysaccharide), chitin (Polymer), cellulose, chitosan, α-glucans, galactomannans, galactosaminogalactan and pigments are components of fungal cell walls. Fungal biomass is more easily generated on a large scale using straightforward fermentation procedures at a relatively low cost, in contrast to yeast, algae, and plants. FTIR study on Mucor rouxii fungi suggests that the presence of amine and phosphate groups contributed most to the biosorption of Pb, Cd, Ni, and Zn ion (Ali Redha, 2020).

Using *Aspergillus niger fungi*, (isolated from electroplating industry effluent), 97% removal of Pb(II) ions was observed (Dhaka et al., 2025). Myconanotechnology" is a promising field that employs fungal biomass for the making of nanoparticles. Fungal species, including Penicillium, Aspergillus, Alternaria, Chrysosporium, Cladosporium, Candida, Cryptococcus, Neurospora, Fusarium, Trichoderma, Pleurotus, Agaricus, Coriolus, Ganoderma, Verticillium, etc., are broadly employed in nanoparticle synthesis (Meera et al., 2025).

4.4 Plant

Plants have been employed as biosorbents for the reuse and recycling of waste products from the food and agricultural sectors. Consequently, plant materials are inexpensive. The cell walls of plants contain a cellulosic matrix, which is known to have carboxylic or phenolic functional groups or cellulose-related components, such as lignin and hemicellulose, which are primarily responsible for the potential of plant biosorbents. The binding of a metal ion with a functional group causes biosorption, which removes the metal ions from the medium based on cation exchange between functional groups and metal ions (Abdel -Aty *et al.*, 2013). It was discovered that the carboxyl, carbonyl, and hydroxyl groups promoted metal binding when Aloe vera waste was employed as a biosorbent to remove uranium and cadmium from water (Kapashi *et al.*, 2019). Mango seed cover with kernels and jamun seed cover with kernels removed lead to 94.85% and 92.78%, respectively (Pal et al., 2022).

4.5 Yeast

Yeast is a topic of interest in biosorption, as several studies have been successfully conducted (Danouche *et al.*, 2021). The most significant commercial yeasts belong to the Saccharomyces genus, specifically baker's and brewer's yeasts. With basic growing media, they are non-pathogenic, simple to cultivate, and provide high biomass production. A literature review reveals that yeast biomass may be efficiently consumed as a biosorption agent for metals such as Au, Ag, Cd, Cu, Ni, Pb, Cr, and radioactive metals such as Th and U (Danouche *et al.*, 2021). Yeasts such as Candida, Saccharomyces, and Pichia are effective biosorbents for metals like Pb, U, Hg, and Cd (Jamir et al.,2024). Most yeasts can be selective to one metal or can sorb a broad category of metals (Ahmed *et al.*, 2022).

4.6. Moss and Lichen:

Some lichen species, along with mosses, have been widely investigated for their ability to adsorb heavy metals from the environment (A *et al.*, 2022). Lichens, which are composite plants made up of fungi and algae, are thought to be an indication of the quality of the environment because of their capacity to absorb and hold onto a wide range of pollutants, including heavy metals and radionuclides (Boruah et al., 2024). The batch approach was used to assess the capacity of lichen biomass (Xanthoparmelia conspersa) to remove mercury(II) ions from aqueous solutions via biosorption. kinetic studies were carried out, which revealed that it followed second-order kinetics, whereas ΔG^o, ΔH^o, and ΔS^o indicated that the process was exothermic. Living lichens such as R. fraxinea accumulate metals across their surfaces (Lestari *et al.*, 2020). An investigation on seven different types of moss species growing in the area of the Bory stobrawskie forest (southern Poland) was carried out in the laboratory. The study revealed that the sorption of Zinc (Zn) and Cadmium (Cd) depends on moss species, and the percentage sorption increases in the following order: *P. commune* < *L. glaucum* < *Eurhynchium praelongum* < *T. tamtariscifolium* ≤ *D. scoparium* ≤ *P. schreberi* < *Sphagnum* sp. (Klos et al., 2014)

Comparison of the biosorption efficiency of different biosorbents shows that **fungi and plants exhibit the highest efficiency**, followed by bacteria and algae (Figure 2).

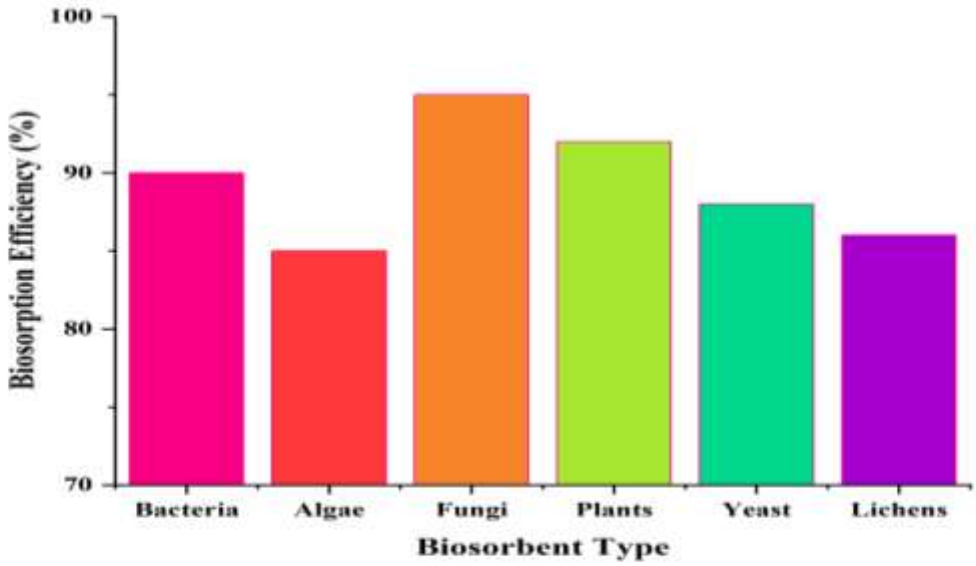


Figure 2: Biosorbent type and its biosorption efficiency %

A trend line graph (Figure 3) indicates how biosorption efficiency has increased over the years for different biosorbents. The data implies that fungi and plants have exhibited the most consistent increase in efficiency, followed by bacteria and algae.

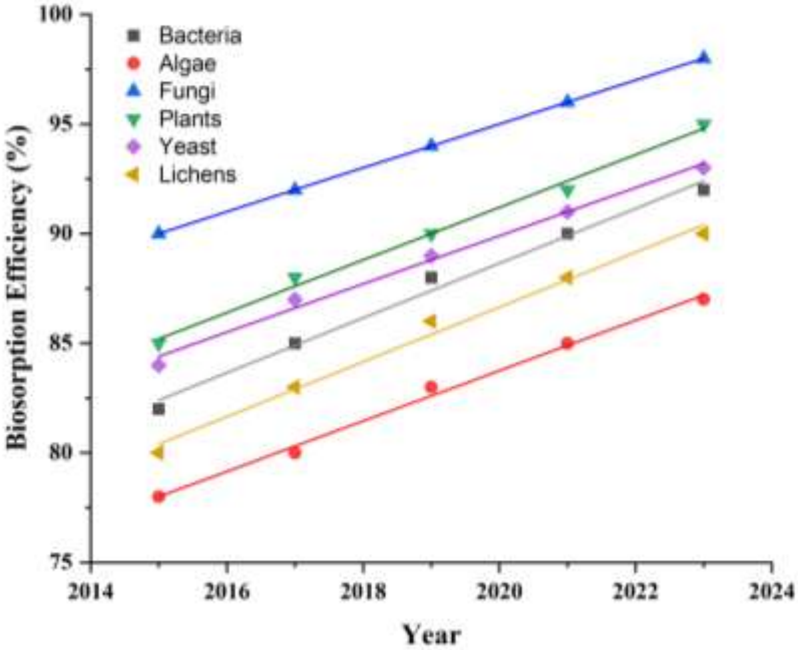


Figure 3: Trend line graph indicating biosorption efficiency

The scatter plot (Figure 4) shows the relationship between pH levels and biosorption efficiency for different biosorbents. It highlights that fungi and plants exhibit higher biosorption efficiency across a wide pH range, while bacteria and algae show optimal performance in neutral to slightly acidic conditions

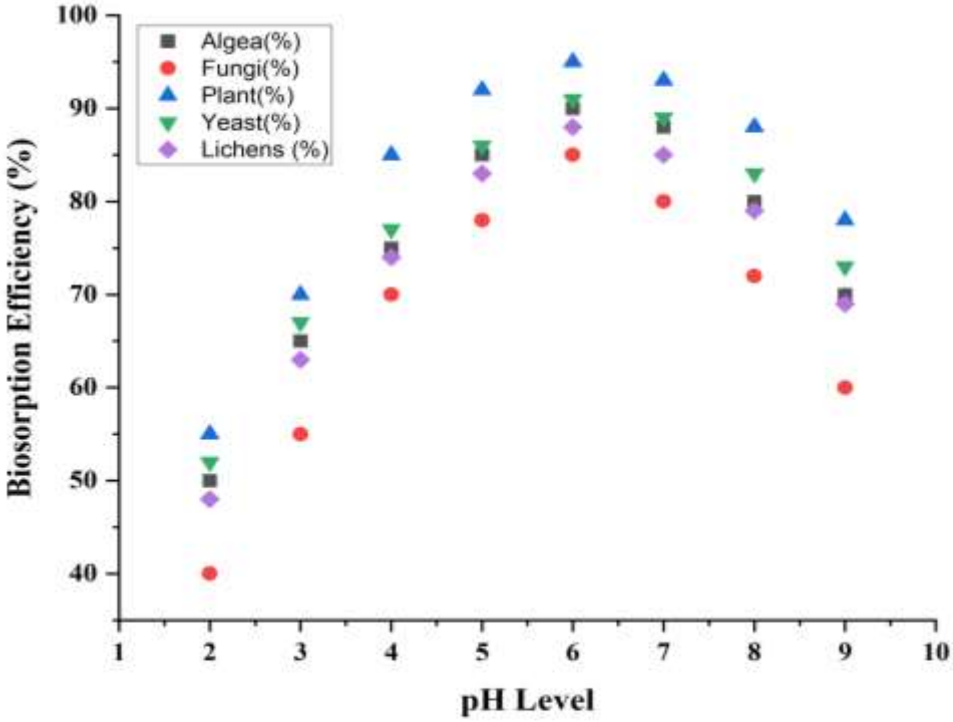


Figure 4: Influence of pH on biosorption efficiency

Pie chart (figure 5) demonstrates the impact of different biosorbents to overall biosorption. Fungi (30%) and plants (28%) give the most, while bacteria (22%) and algae (20%) play slightly smaller roles.

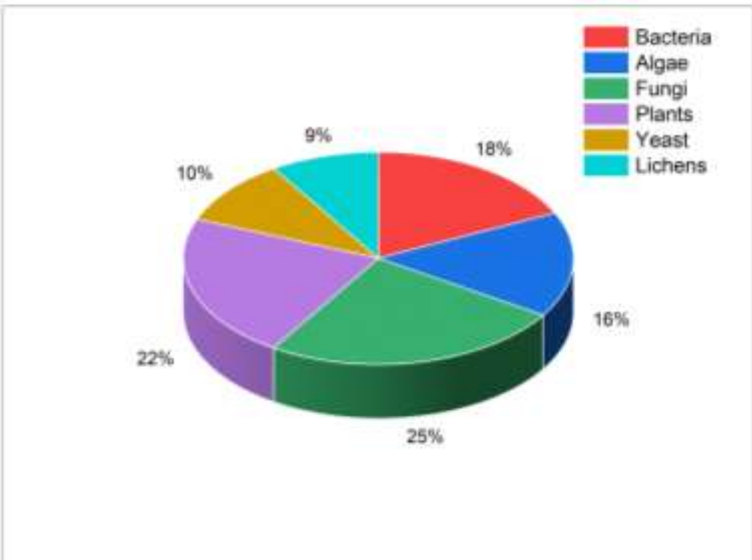


Figure 5: Impact of different biosorbents on overall biosorption

Using a predictive regression model, the biosorption efficiency of fungi—the best-performing biosorbent—shows a rising tendency over time. Future developments in biosorption methods may further increase efficiency, as seen by the black regression line, which shows a consistent improvement (figure 6).

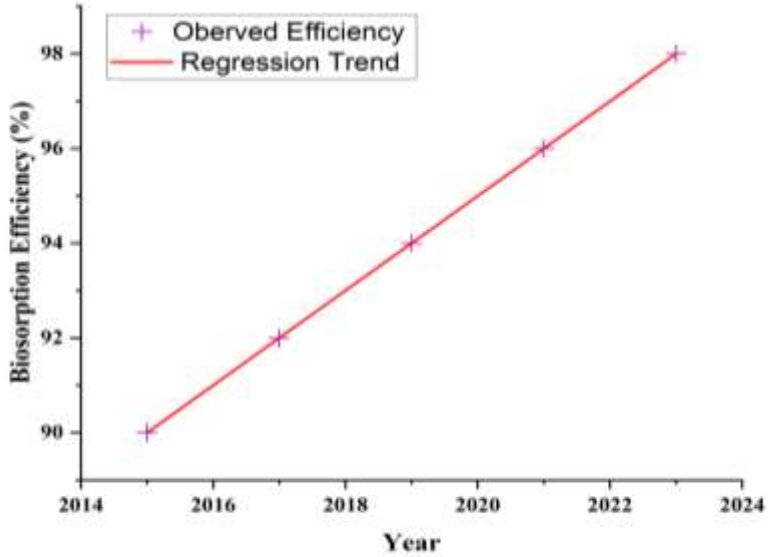


Figure 6: Regression model to predict biosorption efficiency trends

5. Biosorption of selected heavy metals

Heavy metals, including lead (Pb), chromium (Cr)(VI), arsenic (As), cadmium (Cd), and mercury (Hg), are non-threshold poisons that may cause harm even at low doses (Chen et al., 2023; Campbell, 2023). These are toxic heavy metals (THMs) and are the most hazardous heavy metals. Owing to several industrial operations, as well as some natural operations, the environment is heavily contaminated. Elevated levels of heavy metals in many natural systems, including the atmosphere, pedosphere, hydrosphere, and biosphere, have recently emerged as a worldwide concern. THMs severely damage a wide range of plants, animals, and microbes (Gupta et al., 2022). Human exposure to THMs can cause serious health issues, impairments, and in rare circumstances, death in certain extremities (Gupta, 2024). Heavy metals must be eliminated from wastewater and effluents before their release into the environment, owing to their toxicity, and to ensure that they meet safe discharge regulations (Liberti, 2024). The discharge limit set for the above-listed metals: Lead (Pb) = 0.01mg/L, Chromium (Cr) = 0.05 mg/L, Arsenic (As) =0.01 mg/L, Cadmium (Cd)=0.003mg/L, and Mercury (Hg)=0.006mg/L (BIS, 2012).

5.1. Biosorption of Arsenic (As)

Arsenic is a naturally occurring element that often exists in two forms: organic and inorganic. More harmful inorganic arsenic compounds are frequently present in food and water, and can seriously harm human health (Rahaman *et al.*, 2021).

Table 1. Biosorption capacity of different biosorbents for the removal of Arsenic ions from aqueous media

Adsorbent	**Biosorbent type**	**Temperature (°C)**	**pH**	**Metal ion**	**% Adsorption OR Adsorption capacity (mg/g)**	**Reference(s)**
Bacillus thuringiensis strain WS3, Pseudomonas stutzeri strain WS9	Bacteria	37	7.0	As (III) As (V)	95%, 98%	Altowayti *et al.*, (2020)
Bacillus sp. KL1,KL4, KL6	Bacteria	40	5.0	As(V)	77% , 91.66%, 88%	Taran *et al.*, (2019)
Bosea sp. AS-1	Bacteria	35	7.0	As (III)	99%	Lu *et al.*, (2018)
Chlorella vulgaris	Algae	2	6.0	As (III)	93%	Alharbi *et al.*, (2023)
Ulva reticulata	Algae	-	4.0	As (V)	59.5%	Senthilkumar *et al.*, (2020)
Chlorella vulgaris	Algae	50	6.0	As (V)	13 mg/g	Ghayedi, Borazjani and Jafari, (2019)
Indigenous fungi	Fungi	27±2	6.0	As	70 mg/g	Jaiswal *et al.*, (2018)
Aspergillus spp APR-1 and APR-2	Fungi	40	2.0	As (III)	53.94%	Tanvi *et al.*, (2020)
Talaromyces sp.	Fungi	30	6.0	(As)	70 %	Nam *et al.*, (2019)
Mucor circinelloides	Fungi	25	6.0	(As)	29.4 mg/g	Li *et al.*, (2021)
Warnstorfia fluitans	moss	20	6.5	(As)	90%	Sandhi, Landberg and Greger, (2018)
Saccharomyces cerevisiae	Yeast	35	5.0	As (III)	62.90 mg/g	Wu *et al.*, (2012)
Saccharomyces cerevisiae	Yeast	25	7.0	As (III) As (V)	66.2%, 15.8%	Hadiani, Khosravi-Darani and Rahimifard, (2019)
Psychrotolerant Yersinia sp. Strain	Yeast	30	7.0	As (III)	96%	Asadi Haris *et al.*, (2018)
Bacillus thuringiensis	Yeast	37	7.0	As (III)	10.94 mg/g	Altowayti *et al.*, (2019)
Cassia fistula pods	Plant	30	6.0	As (III)	91%	Giri *et al.*, (2022)
Leaves of Tectona Lagerstroemia speciosa	Plant	25	6.0	As(V)	94.6%	Verma & Singh, (2019)

Industries such as mining, smelting, and pesticide production can release arsenic into the environment. (Bundschuh *et al.*, 2021; Khatun and Intekhab, Ashad, 2022) Which in turn contaminates nearby water bodies, enters the food chain, and causes toxicity in plants and animals (Verma and Prakash, 2022). Table 1 depicts the potential of the different biosorbents. It causes toxicity through several methods. Oxidative stress causes the body to produce reactive oxygen species (ROS), damaging lipids, proteins, and DNA.(Hu *et al.*, 2020; Kumar, 2021). Arsenic exposure causes enzyme inhibition, resulting in cellular malfunction and death by inhibiting the vital enzymes required for DNA repair and cellular respiration. (Mukherjee and Valsala Gopalakrishnan, 2023). Prolonged exposure to arsenic leads to epigenetic modifications changing gene expression without affecting the DNA sequence, which may result in cancer. (Mukherjee and Valsala Gopalakrishnan, 2023). Acute exposure leads to gastrointestinal distress, hypertension, skin diseases, and headaches.
As has been extracted from aqueous solutions using blue pine, walnut shells, and chickpea test (Bibi *et al.*, 2017). Blue-green algae and the cyanobacterium Spirulina sp. may be used to extract arsenic from polluted waterways. At pH 6, the highest sorption capacities of both dead and live spirulina were 402 and 525 mg/g, respectively.

5.2. Biosorption of Cadmium (Cd)

Cadmium (Cd) is hazardous to both the environment and human beings. Cadmium, present in the atmosphere, water, and food, when exposed to low concentrations of Cd, causes serious health problems.

Cd exposure through water, air, and soil results in Cd toxicity, which can affect the respiratory system, bones, kidneys, and reproduction, and, in some cases, can lead to cancer in humans. Low concentrations of Cd are highly toxic and carcinogenic to plants. (Hayat *et al.*, 2018). Cadmium can bind to ligands such as cysteine, glutamate, histidine, and aspartate in the human body, which can result in iron deficiency (Burnase, Jaiswal and Barapatre, 2022). Cd can induce hepatotoxicity when it binds to cysteine-rich proteins such as metallothionein in the liver. Mining, alloys, batteries, paint pigments, smelting, electroplating, and fertilizer sectors are sources of Cd. The biosorption capacities of several biosorbents investigated for the removal of Cd ions are compared in Table 2.

Table 2. Biosorption capacity of different biosorbents for the removal of Cadmium ions from aqueous media

Adsorbent	Biosorbent type	Temperature (°C)	pH	% Adsorption OR Adsorption capacity (mg/g)	Reference(s)
Bacillus subtilis	Bacteria	30	4.0	83.5%	Devatha and S, (2020)
Pseudomonas fluorescens	Bacteria	32.7	6.01	90%	Rahman *et al.*, (2022)
Bacillus subtilis	Bacteria	30	4.0	83.5%	Devatha and S, (2020)
Pseudomonas fluorescens	Bacteria	32.7	6.01	90%	Rahman *et al.*, (2022)
Halomonas BVR 1	Bacteria	-	8.0	12.023 mg/g	Manasi *et al.*, (2014)
Chlorella sp.	Algae	-	7.8–8.0.	59.67%	Mátyás *et al.*, (2018)
Ulva lactuca sp.	Algae	25	5.0	43.12 mg/g	Ghoneim *et al.*, (2014)
Caulerpa fastigiata	Algae	25	5.5	92.01%	Sarada *et al.*, (2014)
Sargassum polycystum	Algae	25	4.65	86.20 mg/g	Jayakumar *et al.*, (2022)
Phlebia brevispora	Fungi	25	7.0	91.6%	Sharma et al., (2020)
Fusarium solani	Fungi	28 ± 1	10.0	92.4%	Kumar *et al.*, (2019)
Phanerochaete chrysosporium	Fungi	-	4.15	60%	Rudakiya *et al.*, (2018)
Saccharomyces cerevisiae + Alg beads	Yeast	25	6.0	83%	Rivas *et al.*, (2019)
Saccharomyces cerevisiae	Yeast	-	6.0	90%	Arora, (2019)
Xanthate-modified baker's yeast	Yeast	46	8.0	239.80 mg/g	Song *et al.*, (2019)
Hovenia acerba	Plant	25 ± 2	3.0	56.99%	Pyrzynska, (2019)
Murraya koengii	Plant	25	7.0	22.29 mg/g	Mukherjee *et al.*, (2020)
Poplar sawdust	Plant	-	5.0	49.32 mg/g	Cheng *et al.*,(2021)
Corn stalk	Plant	-	7.0	40 mg/g	Chen *et al.*, (2020)
Moringa oleifera (Moringa) seeds	Plant	20 ± 1	3.0	97%	Aziz et al., (2016)

5.3. Biosorption of Chromium (Cr)

According to Chen et al. (2024), chromium (Cr) is a heavy metal that is toxic, carcinogenic, mutagenic, and teratogenic. Hexavalent and trivalent versions are the most common (Itankar & Patil, 2021). The hexavalent form of Cr(VI), which is roughly 500–1000 times more dangerous than the trivalent form, is a major contaminant in both surface water and groundwater due to its high mobility and solubility in aqueous environments (Itankar & Patil, 2022). It can damage the kidneys, liver, and stomach in addition to causing allergic reactions, respiratory problems, and compromised immune systems.

Table 3: Biosorption capacity of different biosorbents for the removal of Chromium ions from aqueous media

Adsorbent	Biosorbent type	Temperature (°C)	pH	Metal ion	% Adsorption OR Adsorption capacity (mg/g)	Reference(s)
Chelatococcus daeguensis	Bacteria	50	7.0	Cr (VI)	88.89%	Fernández *et al.*, (2018)
Klebsiella sp	Bacteria	30	9.0	Cr (VI)	95%	Hossan *et al.*, (2020)
Bacillus amyloliquefaciens	Bacteria	37	6.0	Cr (VI)	79.90%	Ramachandran *et al.*, (2022)
Escherichia coli	Bacteria	37	-	Cr (III)	91.29%,	Wang *et al.*, (2021)
Rhizobium	Bacteria	28±1	-	Cr (III), Cr (VI)	76 %	Srinivas Ravi *et al.*, (2022)
Spirulina platensis	Algae	60	1.0	Cr(III), Cr (VI)	82.5%	Nithya *et al.*, (2019)
Durvillaea antarctica	Algae	45	2.0	Cr (VI)	66.6%	Al-Homaidan *et al.*, (2018)
Scenedesmus quadricauda	Algae	5–35	2.0	Cr (VI)	100%	Daneshvar *et al.*, (2019)
Sargassum filipendula	Algae	60	3.5	Cr (III)	67.5%	da Costa *et al.*, (2022)
Green microalgae	Algae	80	3.0	Cr (VI)	99.75%	Indhumathi *et al.,* (2014)
Aspergillus niger	Fungi	40	3.0	Cr (VI)	>99%	Chatterjee *et al.*, (2020)
Rhizopus sp.	Fungi	30	2.0	Cr (VI)	95%	Espinoza-Sánchez *et al.*, (2019)
Aspergillus flavus CR500	Fungi	20–40	(5.0–9.0)	Cr (VI)	89.1%	Kumar & Dwivedi, (2019)
Aspergillus niger	Fungal Biomass	25	3.0	Cr (VI)	90%	Kanamarlapudi, Chintalpudi and Muddada, (2018)
Penicillium chrysogenum	Fungal Biomass	25	5.0	Cr (VI)	80%	Sheikhi & Rezaei, (2021)
Penicillium sp.	Fungal Biomass	30	4.0	Cr (III)	75%	Sheikhi & Rezaei, (2021)
Cladonia rangiferina	Lichen	25	2.0	Cr (VI)	92%	Pakade, Tavengwa and Madikizela, (2019)
Sphagnum squarrosum	Moss	20	5.0	Cr (III)	75%	Pakade, Tavengwa and Madikizela, (2019)
Moss (Sphagnum spp.)	Moss	25	4.0	Cr (VI)	85.5%	Kabdaşlı & Tünay, (2023)
Lichen (Cladonia spp.)	Lichen	28	6.0	Cr (III)	88.7%	Kabdaşlı & Tünay, (2023)
Saccharomyces cerevisiae	Dead yeast cells	25	4.0	Cr (VI)	85.4%	Saini *et al.*, (2023)
Candida utilis	Live yeast	30	5.5	Cr (III)	92.3%	Saini *et al.*, (2023)

Saccharomyces cerevisiae	Yeast cells	25	2.0	Cr (VI)	83.5%	Acharyya, Das & Thaker, (2023)
Saccharomyces cerevisiae	Immobilized yeast	30	4.0	Cr (III)	78.2%	Arrisujaya *et al.*, (2023)
Kluyveromyces marxianus	Yeast biomass	25	3.0	Cr (VI)	88.0%	Arrisujaya *et al.*, (2023)
Avocado seed	Plant	25	2.0	Cr (VI)	98.5	Sen, (2023)
Wood apple Shell powder	Plant	30	4.0	Cr (VI)	99.8%	Itankar & Patil, (2021)
Prosopis spicegera	Plant	-	2.0	Cr (VI)	97.69 %	Fernández *et al.*, (2018)
Sargassum dentifolium	Plant	50	7.0	Cr (VI)	99.68%	Husien *et al.*, (2019)

The primary industrial sources of chromium include foundries for iron and steel, electroplating, metallurgy, metal finishing, welding of alloys/steel, ceramic manufacturing tanneries, textiles, leather tanning, and inorganic chemical facilities (Nilisha Itankar & Yogesh Patil, 2022). Before releasing the effluent into the environment, the industry must eliminate all traces of chromium.

Experimental studies were carried out to demonstrate the ability of various biomasses to eliminate chromium from aqueous media, and the results are shown in Table 3, which contrasts the biosorption capacity of each biosorbent.

5.4. Biosorption of Lead (Pb)

Lead(Pb) is emitted into the atmosphere by burning fossil fuels, lead compounds, automobile emissions, and companies that use lead (Violante *et al.*, 2010). It usually combines with other elements to generate lead compounds. Lead sulphate, lead carbonates, and lead oxide are the products of the reaction of lead with air and water. Although lead is prevalent, human activity has been identified as the primary reason for rising lead levels in the environment (Hakeem, 2015).

The estimated lead(II) ion concentration released in the environment from the battery sector is 5-66 mg/L, the mining industry is 0.02-2.5 mg/L, and the oil industry is 125-150 mg/L (Tasar et al., 2014). 173.8 Mt of Pb was released into the atmosphere between 1930 and 2010, with the majority coming from the manufacturing (26%), consumption (20%), and waste management and recycling (48%) phases. $PbSO_4$, PbO, Pb, and PbS were the primary species released, accounting for 61.2% of the total emissions (Hettiarachchi et al., 2024).

Animals and plants are considered to be fatally affected by lead. It results in several illnesses in humans, including anaemia, brain damage, mental deficiency, renal damage, encephalopathy, anorexia, cognitive impairment, behavioural problems, and vomiting (Singh *et al.*, 2023). Pb may bioaccumulate in bones over more than 20 years and alter the cellular membrane permeability of organs and haemoglobin production in people when it binds to those

Table 4. Biosorption capacity of different biosorbents for the removal of Lead ions from aqueous media

Adsorbent	Biosorbent type	Temperature (°C)	pH	% Adsorption OR Adsorption capacity (mg/g)	Reference(s)
Bacillus licheniformis	Bacteria	30	6.0	98%	Wen *et al.*, (2018)
Pseudomonas azotoformans	Bacteria	30	6.0	88.58%	Choińska-Pulit, Sobolczyk-Bednarek and Łaba, (2018)
Pannonibacter phragmitetus	Bacteria	30	6.0	49.79 mg/g	Saravanan *et al.*, (2021)
Ralstonia solanacearum	Bacteria	35	6.0	90%	Pugazhendhi *et al.*, (2018)
Mixed- culture of algae	Algae	25 ± 2	6.0	95.43%	Mousavi *et al.*, (2019)
Sargassum muticum	Algae	25	5.0	76 mg/g	Hannachi & Hafidh, (2020)
Cladophora	Algae	-	4.0	20.56 mg/g	Amro & Abhary, (2019)
Talaromyces islandicus	Fungi	30	5.0	90.06%	Sharma *et al.*, (2020)
Rhizopus arrhizus	Fungi	25	4.0	103.70 mg/g	Senol *et al.*, (2021)
Filamentous fungus	Fungi	28	5.0	53.7%	Wang *et al.*, (2019)
Phanerochaete chrysoporium	Fungi	-	5.5	75%	Zhao *et al.*, (2020)
Sphagnum peat moss	Moss	26 ± 2	8.0	97.6%	Lubbad & Al-Batta, (2020)
Guar gum	Plant Material	-	5.0	83%	Mukherjee *et al.*, (2018)
Arundinaria alpina	Plant Material	25	5.0	99.8%	Asrat *et al.*, (2021)
Rice husk, wheat straw, and corncob	Plant Material	-	5.5	96.41%, 95.38%, 96.92%	Amen *et al.*, (2020)
Phytolacca americana L.	Plant Material	25	6.0	93.29%	Wang *et al.*, (2018)
Banana Peels	Plant Material	-	5.0	98.14 %	Afolabi, Musonge & Bakare, (2021)

enzymes (Singh et al., 2023). Pb (II) ions have a strong affinity for thio, oxo, and phosphate groups, which are found in a variety of enzymes and macromolecules in living organisms (Morozanu et al., 2017). Several experiments were carried out to assess the ability of various biosorbents to remove lead (II) ions from aqueous environments; a selection of these investigations, comparing the biosorption capacities of each, are shown in Table 4.

5.5. Biosorption of Mercury (Hg)

According to USEPA, Mercury is a ubiquitous contaminant, a global pollutant that is highly toxic and is readily gathered in ecosystem (USEPA). It has been linked to public health catastrophes in Iran and Japan (Minamata Bay). Exposure to mercury vapours is the primary pathway affecting the human brain and lungs. Mercury poisoning primarily affects the nervous system, kidneys, and immune system. It also endangers aquatic and wild species (Ahmed, Zakiya and Fazio, 2022).

It's salts, such as mercurous and mercuric salts, attack the gut lining and kidney. According to WHO, the main sources of exposure include degassing of mercury from dental amalgam, consumption of contaminated fish, and other seafood. It enters by multiple pathways, both natural and anthropogenic, and contaminates the ecosystem air, water, and soil. Natural forest fires, weathering of mercuriferous regions, degassing from surface water and the Earth's crust through volcanic eruptions, and biogenic emissions are all sources of naturally occurring mercury emissions into the environment (Gworek, Dmuchowski and Baczewska-Dąbrowska, 2020). Mercury pollution also originates from human activities, such as agriculture, battery manufacturing, burning fossil fuels, mining and metallurgical processes, paint and chloralkali

Table 5. Biosorption capacity of different biosorbents for the removal of Mercury ions from aqueous media

Adsorbent	Biosorbent type	Temperature (°C)	pH	% Adsorption OR Adsorption capacity (mg/g)	Reference(s)
Pseudomonas putida	Bacteria	30	8.0	99.72%	Zhao *et al.*, (2021)
Klebsiella sp. NT8 and Bacillus sp. NT10	Bacteria	25	6.0	2597.62 , 2617.23 mg/g	Xia *et al.*, (2020)
Live or dead biomass of A. marina SSS2	Bacteria	35	7.0	87%, 95%	Mukkata *et al.*, (2019)
Chlorella vulgaris	Algae	35	6.0	95.5%	Kumar, Singh, and Sikandar, (2020)
Ulva intestinalis, Ulva lactuca, Fucus spiralis, Fucus vesiculosus, Gracilaria sp., Osmundea pinnatifida	Algae	Room Temp.	8.5	87.2 %, 94.0 %, 88.0 %, 93.0 %, 86.0 %, 87.7 %	Fabre *et al.*, (2020)
Ulva lactuca Linnaeus	Algae	22.2	4.0	96.1% ± 0.7	Çetintaş *et al.*, (2022)
Sargassum crassifolium	Algae	Room Temp.	9.0	98%	Putri and Syafiqa, (2019)
F. velutipes	Fungi	Room Temp.	7.0	69.35%	Li *et al.*, (2018)
Saccharomyces cerevisiae	Fungi	25	5.4	89%	Hadiani *et al.*,(2018)
Penicillium sp.	Fungi	60	4–5.0	99.6%	Sánchez-Castellón *et al.*, (2022)
Saccharomyces cerevisiae	Yeast	25	5.4	88.9%	Hadiani *et al.*,(2018)
Roasted Date Pits	Plant material	25	6.0	95 %	Al-Ghouti *et al.*, (2019)
Pine biochar	Plant material	25	5.0	1641 mg/g	Johs *et al.*, 2019)
Coffee waste	Plant material	33	7.00	97%	Mora Alvarez *et al.*, (2018)
Thymus schimperi	Plant material	25	7.0	90%	Geneti *et al.*, (2022)

industries, and wood pulping. Other significant sources of mercury pollution include thermometers, electronic devices (LEDs, CFLs), wiring and control devices, the paper and pulp industries, and oil refining (Kumar et al.,2020).

In a recent study on *Lentinus edodes, U. lactuca,* and *Typha domingensis*, the mercury removal efficiency was found to be 100-337 mg/g (Rani, Srivastav and Kaushal, 2021). According to research on biosorption, the hydrocolloid Gum Karaya had a maximum biosorption capacity of 62.5 mg/g and suited the Langmuir isotherm ($R^2 > 0.999$)(Padil et al., 2021). Experimental results showed that algal biomass (Cristoseira baccata) removed 178 mg/g of Hg^{2+} at 4.5 pH and 329 mg/g at 6 pH. In batch mode, it was found that lichen biomass (Xanthoparmelia conspersa) removed 82.8 mg/L of Hg^{2+} ions. In laboratory settings, Pseudomonas aeruginosa was found to exhibit a Hg^{2+} bioremediation capability of 62% (Tanwer et al., 2022).

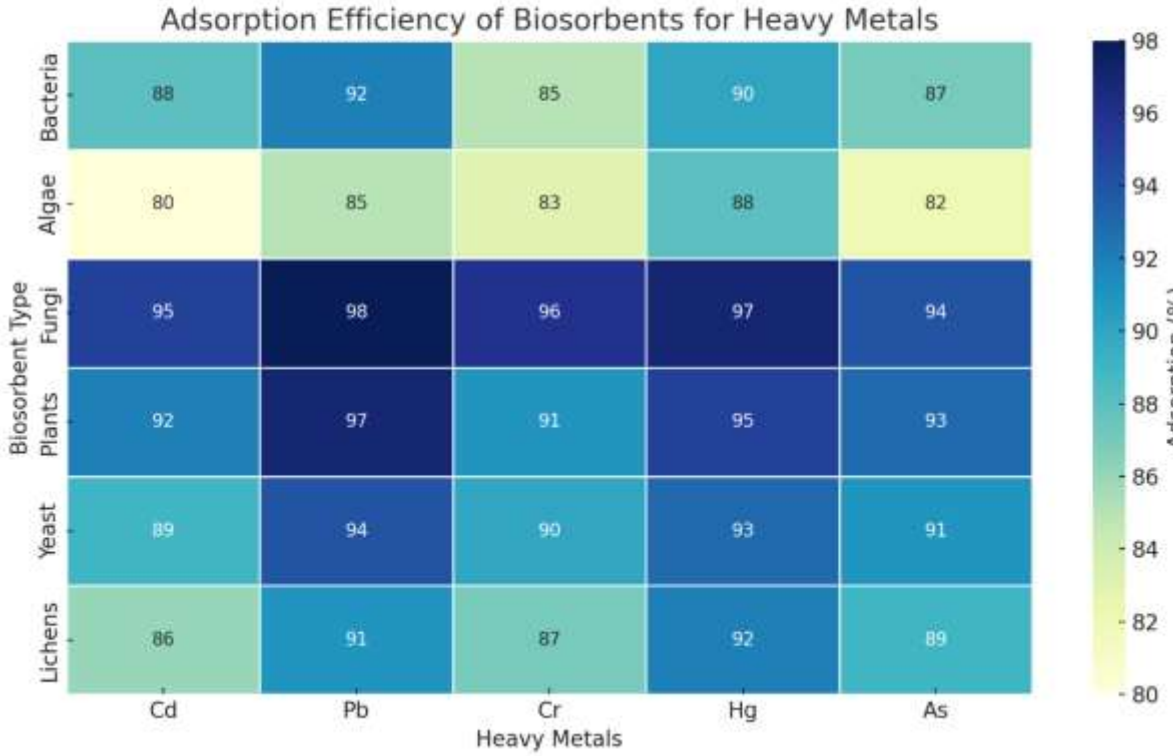


Figure 7: Heavy metals adsorption by different biosorbents

Figure 7 shows the heat map that summarizes the function of different biosorbents towards different metals, displaying the percentage adsorption capacity. It demonstrates the biosorption efficiency of different biosorbents for several heavy metals. The darker shades suggest higher efficiency, with fungi consistently achieving the best across all metals, followed by plants, bacteria, and algae.

6. Factors affecting biosorption capacity

Numerous crucial operational and physicochemical factors regulate biosorption, such as pH, contact time, initial metal ion concentration, temperature, and biomass quantity. As covered below (Table 6), these have an impact on how metal ions and biosorbent functional groups interact.

Table 6. Factors affecting biosorption

Parameters	Effect on Biosorption	Optimal Range / Observation	Reference(s)
pH	Regulates metal ion speciation and charge on biosorbent surfaces. Protonation of binding sites at low pH decreases biosorption	Optimal range: 4–7; Precipitation at higher pH	Gadd (2009), Priya et al. (2022), Bilal et al.,2018
Temperature	Affects biosorption kinetics and thermodynamics. Exothermic processes show decreased removal at higher temperatures	20–35°C stable for most biosorbents	Ali Redha (2020), Bilal et al., (2018)
Contact Time	Establishes the time required for equilibrium to be achieved. Greater contact enhances uptake up to the saturation point	60–120 minutes; not significantly altered after equilibrium	Nemeş & Bulgariu (2016)
Biomass Dose	Increases the number of binding sites present. Too high a dose causes site overlap or aggregation	0.5–6.0 g/L	Avanzi et al., (2014), Ali Redha (2020)
Initial Metal Concentration	Determines saturation level and helps assess biosorbent capacity	5–200 mg/L	Al-Azzawi et al., (2013)
Other Factors	Surface area, Functional groups present on biomass, particle size, porous nature, agitation, and pre-treatment affect efficiency	Modified biomass increases biosorption	Kumar et al., (2020), Agoun & Avci (2024)

6.1. Other factors

Surface properties including surface functional groups, surface area, pore size distribution, and particle size all play an important role in determining biosorption efficiency. Functional groups involving carboxyl, hydroxyl, amino and sulphuryl groups have been found to be active in metal ion binding as evidenced using FTIR analysis in Chlorella vulgaris biomass for mercury removal. Increased surface areas and optimal pore sizes enhance metal ion capture, while smaller sizes improve the ratio of surface area to volume, further boosting sorption. Powdered forms excelled over dried leaves in extracting Zn, Pb and Cu ions in a study involving lettuce leaves, indicating that particle size is crucial. The presence of more than one metal ion causes competition for binding sites and hence a reduction in sorption, depending on the affinity of each ion to the biosorbent. Agitation enhances interaction between metal and biomass but be carefully controlled to avoid fracturing particles. Pre-treatment processes involving washing, modification by chemicals (acid/base/surfactant treatment), and physical treatment (drying and grinding) change surface properties and improve biosorption capacity. Chemically altered biosorbents have been found to exhibit significantly improved performance; for example, grafted copolymer-treated orange peel exhibited 4.2 to 16.5 higher biosorption capacity for Pb^{2+}, Cd^{2+} and Ni^{2+} ions as compared to untreated material, demonstrating strongly the efficacy of modifying surfaces to improve metal capture orange peel.

7. Desorption

Metals are precious, and desorbing agents help in the removal of biosorbed species (metal ions) from the biosorbent surfaces. The recovered metal species can be reused in the industry, and biosorbents can be reprocessed (Bayuo et al., 2024; Raji et al., 2023; Patil, 2021).

Desorption is the step adopted by most researchers after biosorption. Desorption can be performed by removing the biosorbed metal ions utilizing a desorbing agent, which enables the reuse of the exhausted biosorbent (Bauyo et al., 2024; Calero et al., 2013). However, challenges related to the loss of biosorption efficiency after regeneration have not been thoroughly studied.

The following formula is used to compute the proportion of desorbed species:

$\%Desorption = (q_{desorbed}/q_{adsorbed}) \times 100$

Where:

- $q_{desorbed}$ = amount of substance desorbed (released) from the material (in appropriate units such as moles, grams, etc)
- $q_{adsorbed}$ = the amount of substance originally adsorbed onto the material

A high desorption percentage indicates a higher degree of biosorbent regeneration for future usage; this should be considered when selecting a biosorbent to increase sustainability.

Desorbing agents are typically categorized into three groups: chelating agents (EDTA, ethylenediaminetetraacetic acid), alkalis (sodium hydroxide, sodium hydrogen carbonate, potassium hydroxide, and hydrochloric acid), and acids (hydrochloric acid, sulphuric acid, nitric acid, and acetic acid) (Calero *et al.*, 2013). In terms of speed and desorption %, acidic desorbing agents have been reported to be more effective than basic and neutral agents (Calero *et al.*, 2013). As indicated in Table 7, Desorption efficiencies of heavy metals varied from 50.29% to as high as 99.99%, with EDTA and HCl proving to be most efficient. Reusability was in a range from 3 to 10 cycles, reflecting a high regeneration potential in various biosorbents such as cryogels and modified silicas. High desorption (>85%) was often found for Pb(II) as well as Cd(II) with potential recovery by low-concentration acids

Table 7. Desorption Efficiency and Reuse Potential of Different Adsorbents in Heavy Metal Ion Recovery

Heavy Metal	Type of absorbent	Desorbing agent	Desorption (%)	Reuse cycle	Reference(s)
Cr(VI) , Pb(II)	Groundnut husk	HCl and H_2SO_4	76.1, 82.1	5	Bayuo, Abukari and Pelig-Ba, (2020)
Pb(II)	Magnetic bentonite (M-B)	1.00 mol/L $NaNO_3$	90.21	6	Zou *et al.*,(2019)
Cu(II), Cd(II), Pb(II), Ni(II)	A-MIL-121	80 °C in water	90.0	10	Ji *et al.*, (2021)
Zn (II)	Mango leaf powder	0.1mol/L HCl, 0.1mol/L HNO_3	94.7, 89.5	3	Kaushal, (2023)
Cd (II)	Soil + humic acid	0.05 M EDTA	50.29	3	Zheng *et al.*, (2022)
Cu(II)	Poly(vinyl imidazole) cryogel	0.1 M Na_2 EDTA and 1 M HCl	99.99	5	Zhong *et al.*, (2021)
Hg(II)	Sulfhydryl-modified SiO_2 cryogel	1 M HCl	89.0	5	Zhu *et al.*, (2021)
Cd(II) Pb(II)	MgO-SiO	0.05 M HCl	84.5, 89.9	-	Ciesielczyk, Bartczak and Jesionowski, (2016)
Pb(II)	Brown macroalga Sargassum ilicifolium	0.2 M HCl	88.0	3	Tabaraki, Nateghi and Ahmady-Asbchin, (2014)
Cd (II)	Araucaria heterophylla	2 N HCl	84.45	4	Sarada *et al.*, (2017)
Cd (II)	Mealworm frass (MF).	0.02 M HCl	90.0	5	Kim *et al.*, (2025)

Analysis of Biosorption

The biosorption performance of plants, fungi, algae, and bacteria for the removal of various heavy metals, such as As, Cd, Cr, Pb, and Hg, was studied. Biosorption exhibits good adsorption effectiveness, is economically viable, and is simple to use and operate (Torres, 2020). Waste, such as agricultural residues, agro-industrial wastes, dairy waste, industrial waste,
and leftover plant materials (such as peels, seeds, skin, shells, and stones) can be converted

into biomass (Taneja et al., 2023). These wastes, which are viewed as trash, can be acquired without charge. In developing nations with limited technological advancements, biosorption techniques are highly beneficial. Another benefit of plant-based biosorbents is that they reduce the biological and/or chemical sludge (Hassan et al., 2020). In addition to providing the possibility of metal recovery for various industrial applications, several types of biosorbents have the ability to both desorb and regenerate, making their use compatible with sustainable development. Much research has looked at the removal of one or two metals through biosorption; however, the results of these studies may not be applicable in real-world situations because contaminated water might contain a wide range of heavy metals. Additionally, organic pollutants may be present in water, which could alter the composition of metal ions and the biosorption process. One recommended step in biosorption research is to look at how lab results are applied to real contaminated water samples (Nathan et al., 2022).

For instance, it would be difficult to maximize the water pH in practical settings, despite it being the most important component. The biosorption capabilities of biosorbents measured for particular pH values in laboratory settings might not be accurate in real life because there are many other environmental factors that affect pH (Fertu et al., 2022). The intricacy and matrix structures of polluted water were typically not reflected in the tested water samples.

Furthermore, the removal of heavy metals is the primary goal of the majority of biosorption research; nevertheless, the removal of hazardous organic pollutants has not received much attention. Actually, a lot of studies focus on removing heavy metals in their cationic state rather than their anionic form (e.g., CrO_4^{2-}).
Early biosorbent saturation may be one of the drawbacks of biosorption processes; therefore, biosorbents need to be changed often. The recovered metal must be carefully disposed of or used when the saturated biosorbent is desorbed from the biosorbed metal.

The efficiency of the recycled or repurposed biosorbent and the desorption procedure are also negotiable. According to the Scopus database, 16,202 publications on the subject of "biosorption" were released between 1970 and December 4, 2024. Unfortunately, companies have not yet brought biosorbents to the market (Gadd, 2009). Industries often choose the use of oxidation-reduction methods, reverse osmosis, ion exchange, and chemical precipitation (Wang et al., 2021).

Chemical precipitation is preferred because it is highly effective in removing a variety of heavy metals, even if it is not selective (Pohl, 2020). However, this process generates a large amount of solid sludge, which is detrimental to the environment (Fei & Hu, 2023). Another challenge for the industrial use of biosorption is that existing methods, such as ion exchange and precipitation, are well-established in their processes and have proven to be suitable on a large scale. Industries may find it unsafe and unfeasible to adopt new procedures in place of established ones.

The fundamentals of the main factors affecting biosorption efficacy have been established, including the effects of different experimental settings, batch and continuous process operations, and the manner in which different kinds of biosorbents absorb metals. The next stage is to apply this economical and effective technique in a business context. Researchers should carry out further research for this reason.
It is more difficult to scale up the continuous biosorption process to pilot or industrial scale due to the behavior of biosorbents in real industrial effluents.

Conclusion and future perspectives

A low-cost, sludge-free, and environmentally friendly substitute for traditional heavy metal cleanup techniques is biosorption. It works by complexation, ion exchange, and physical adsorption; biosorbents with strong metal-binding capabilities include fungi and brown algae. However, despite extensive lab-scale research that frequently utilizes synthesis solutions, biosorption still faces critical challenges in real-world applications, such as variability in wastewater composition, biosorbent stability, and scalability.

To advance biosorption from experimental to practical application, the following research gaps and future directions must be addressed:

- **Real wastewater validation**: Evaluating the performance of biosorbents using real industrial effluents to reflect complex matrices.
- **Pilot-scale and commercial trials**: Demonstrating scalability, economic viability, and process reliability in real settings.
- **Long-term regeneration and reuse**: Evaluating the durability and reusability of biosorbents over multiple adsorption–desorption cycles.
- **Hybrid technology development**: Integrating biosorption with chemical, membrane, or advanced oxidation processes for enhanced performance.
- **Nanomaterial integration**: Improving surface characteristics, selectivity, and adsorption kinetics through nanoparticle functionalization.
- **Multi-metal and competitive ion studies**: Identifying biosorption behaviour in complex, multi-contaminant systems.
- **Standardization and regulatory frameworks**: Establishing guidelines and protocols to support biosorption as a dependable and acceptable technology.

In conclusion, biosorption has great potential as an eco-friendly and effective approach for heavy metal removal. Bridging the gap between laboratory research and field implementation requires interdisciplinary collaboration among researchers, industries, and policymakers to translate biosorption technology into sustainable environmental practice.

Author Contributions

Nilisha Itankar: Conceptualization, writing—original draft preparation, supervision,

Prajakta Magdum: Data curation, writing, and methodology, formal analysis, and validation

All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Acknowledgments

The authors gratefully acknowledge the unwavering support and encouragement provided by Symbiosis Institute of Technology and Symbiosis International (Deemed University). Their continued guidance and resources have been instrumental in the successful completion of this work.

Conflicts of Interest

The authors declare no conflicts of interest.

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