



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

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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 utilises 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 commercialisation of this promising technology.

INTRODUCTION

Environmental pollution due to heavy metals has multiplied from a regional problem to a worldwide one, exacerbated by rising urbanisation, industrialisation, and poor wastewater treatment. Water pollution, which may arise from an array of sources such as agriculture, wastewater, oil spills, and radioactive materials, is among the significant problems that civilisation 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 et al. 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, and people inadvertently endanger their health when they consume contaminated foods such as fish and vegetables. Owing to this 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 standardisation, and clarity

about sorption mechanisms across various biosorbent types, 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.

BIOSORPTION INSIGHT

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

Biosorption using a biomaterial is a two-phase process: one for the mobile or liquid phase and one for the stationary phase, which in this case is biomass. The mobile phase is usually an aqueous solution of dissolved metal ions or 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 are mainly adsorbed through the cell walls of these biological sorbents (Ali Redha 2020). A variety of biosorbents, such as 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, alcohols, and carbohydrates, and hydroxyl (-OH) groups (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.

$$\% \text{Removal of Cr(VI)} = \frac{C_{\text{initial}} - C_{\text{final}}}{C_{\text{initial}}} \times 10 \quad \dots (1)$$

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

$$Q = \frac{(C_0 - C_e) V}{m} \quad \dots (2)$$

Where

- C_f : Final concentration of Cr(VI) in solution (mg.L^{-1})
- C_i : Initial concentration of Cr(VI) in solution (mg.L^{-1})
- C_0 : Initial concentration of Cr(VI) in solution (mg.L^{-1})
- C_e : Concentration of Cr(VI) in solution at equilibrium (mg.L^{-1})
- V : Volume of the solution (L)
- m : Mass of biomass (g)
- Q : Metal uptake or adsorption capacity (mg.g^{-1})

(Singh et al. 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).

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 the nature and number of binding/reactive sites, accessibility and availability of binding sites, and the affinity between the binding site of the biosorbent and the concerned metal ion, which 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.

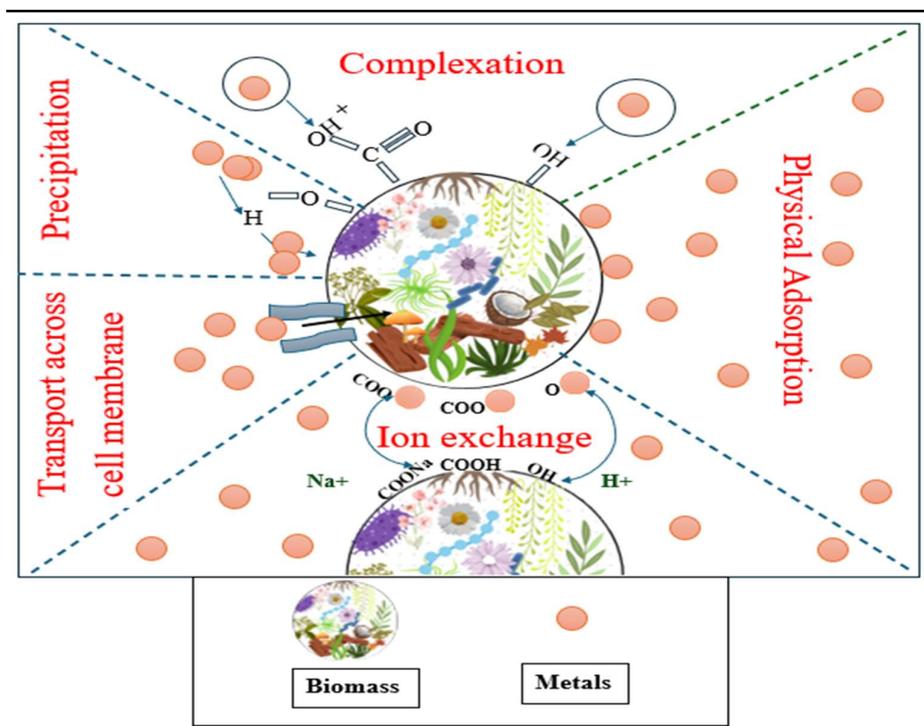


Fig. 1: Mechanism of biosorption.

Biosorption mechanisms include ion exchange, physical adsorption, chemical adsorption, precipitation, complexation, and electrostatic interactions (Javanbakht et al. 2014, Alavi & Zilouei 2014). 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.

Biosorption can be (i) metabolism-dependent or (ii) non-metabolism-dependent according to biomass activity. The non-metabolic mechanism is depicted in Fig. 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 complexation 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 et al. 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 et al. 2018).

Physical Adsorption

Physical adsorption is one of the major biosorption processes, in which adsorbates attach to biosorbent surfaces by weak interactions such as van der Waals forces, dipole-dipole interactions, 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, and the 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 produced through hydrothermal liquefaction have been used to remove Pb from water, affirming the efficiency of physical adsorption in metal recovery processes. These results confirm the relevance of surface functional groups as well as environmental parameters to guarantee optimal physical adsorption for treating wastewater.

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 the release of lighter ions such as sodium, potassium, magnesium, and calcium (Abdi & Kazemi 2015, Volesky and 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 relatively low pH levels, while electrostatic interaction dominates at relatively high pH levels.

The interaction between lead ions and functional groups such as hydroxyl and carboxyl 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 such as carboxyl, phosphate, and hydroxyl groups on their surface (Kanamarlapudi et al. 2018). Such findings exhibit the diversity of ion exchange in biosorption processes across different biosorbents and environmental conditions.

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. Chelation is an advanced form of complexation where an organic ligand forms covalent bonding with the metal ion from multiple directions and results in a 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, and is the most crucial parameter in complexation.

For being of a soft acidic type, lead selectively covalently binds to biosorbent organic ligands that bear soft bases like nitrogen or sulphur. Moreover, borderline-classified ions like manganese, zinc, cadmium, as well as copper, also possess a high affinity to form compound's complexes with organic compounds that bear nitrogen or sulphur (Afolabi et al. 2021). But the availability and accessibility of that binding site that contains the base's donor atom matter to influence complexation. One can confirm that the 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).

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 the chemical interaction of metal ions with the functional groups of the cell wall of the biosorbent in metabolism-independent biosorption (Kanamarlapudi et al. 2018). Such processes might involve oxidation-reduction reactions.

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.

TYPES OF BIOSORBENTS

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 (Abdi & Kazemi 2015).

Functional groups, including oxygen, nitrogen, sulphur, or phosphorus, commonly facilitate heavy metal biosorption by bacteria. 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 -NH₂ (Liu et al. 2019).

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 a 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. Its 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⁻¹ and 121.95 mg.g⁻¹, 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).

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 (polysaccharides), 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 ions (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).

Plants

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 led to 94.85% and 92.78%, respectively (Pal et al. 2022).

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).

Moss and Lichens

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° , ΔH° , and ΔS° indicated that the process was exothermic. Living lichens such as *R. fraxinea* accumulate metals across their surfaces. An investigation on seven different types of moss species growing in the area of the Bory Stobrowskie 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* \leq *D. scoparium* \leq *P. schreberi* < *Sphagnum* sp. (Kłos 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 (Fig. 2).

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

The scatter plot (Fig. 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.

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

Using a predictive regression model, the biosorption efficiency of fungi-the best-performing biosorbent-shows

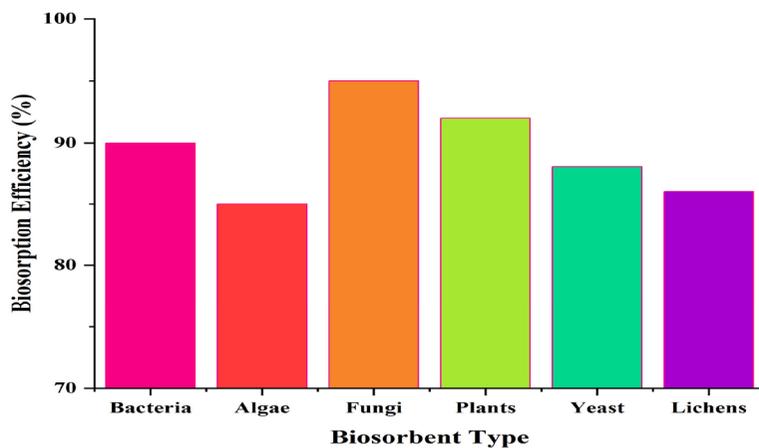


Fig. 2: Biosorbent type and its biosorption efficiency %.

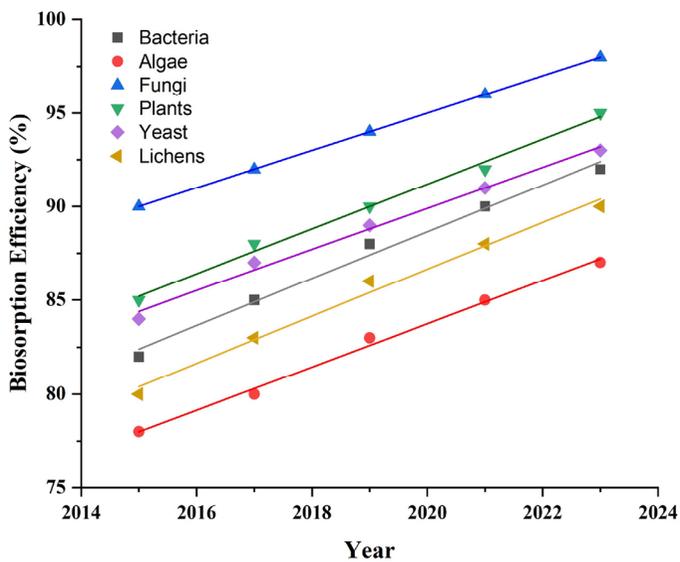


Fig. 3: Trend line graph indicating biosorption efficiency.

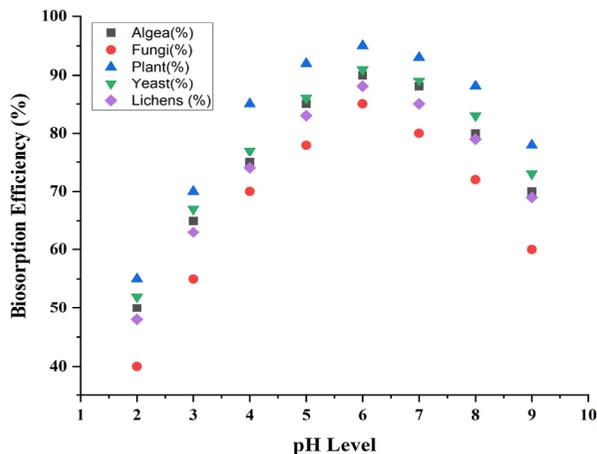


Fig. 4: Influence of pH on biosorption efficiency.

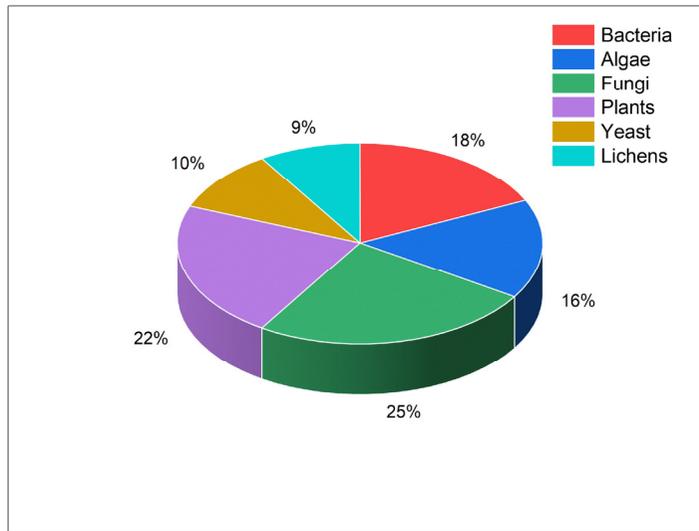


Fig. 5: Impact of different biosorbents on overall biosorption.

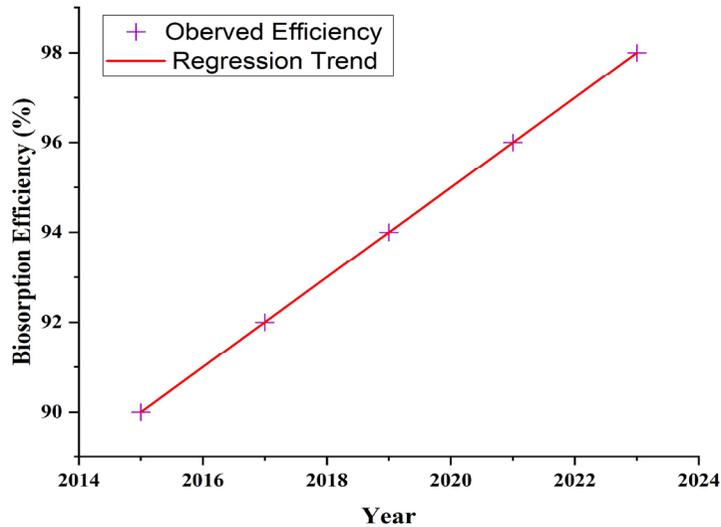


Fig. 6: Regression model to predict biosorption efficiency trends.

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 (Fig. 6).

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) = 0.01 mg.L⁻¹, Chromium (Cr) = 0.05 mg.L⁻¹, Arsenic (As) = 0.01 mg.L⁻¹, Cadmium (Cd) = 0.003 mg.L⁻¹, and Mercury (Hg) = 0.006 mg.L⁻¹ (BIS 2012).

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).

Industries such as mining, smelting, and pesticide production can release arsenic into the environment. (Bunds Schuh et al. 2021, Khatun & Intekhab 2022). This in turn contaminates nearby water bodies, enters the food chain, and causes toxicity in plants and animals (Verma & 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 & 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 & 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⁻¹, respectively.

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.

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

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

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 et al. 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.

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.

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.

Biosorption of Lead (Pb)

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 ⁻¹]	Reference(s)
<i>Chelatococcus daeguensis</i>	Bacteria	50	7.0	Cr (VI)	88.89%	Fernández et al. (2018)
<i>Klebsiella</i> sp.	Bacteria	30	9.0	Cr (VI)	95%	Hossan et al. (2020)
<i>Bacillus amyloliquefaciens</i>	Bacteria	37	6.0	Cr (VI)	79.90%	Ramachandran et al. (2022)
<i>Escherichia coli</i>	Bacteria	37	-	Cr (III)	91.29%,	Wang et al. (2021a)
<i>Rhizobium</i>	Bacteria	28±1	-	Cr (III), Cr (VI)	76 %	Srinivas Ravi et al. (2022)
<i>Spirulina platensis</i>	Algae	60	1.0	Cr(III), Cr (VI)	82.5%	Nithya et al. (2019)
<i>Durvillaea antarctica</i>	Algae	45	2.0	Cr (VI)	66.6%	Al-Homaidan et al. (2018)
<i>Scenedesmus quadricauda</i>	Algae	5–35	2.0	Cr (VI)	100%	Daneshvar et al. (2019)
<i>Sargassum filipendula</i>	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)
<i>Aspergillus niger</i>	Fungi	40	3.0	Cr (VI)	>99%	Chatterjee et al. (2020)
<i>Rhizopus</i> sp.	Fungi	30	2.0	Cr (VI)	95%	Espinoza-Sánchez et al. (2019)
<i>Aspergillus flavus</i> CR500	Fungi	20–40	(5.0–9.0)	Cr (VI)	89.1%	Kumar and Dwivedi (2019)
<i>Aspergillus niger</i>	Fungal Biomass	25	3.0	Cr (VI)	90%	Kanamarlapudi et al. (2018)
<i>Penicillium chrysogenum</i>	Fungal Biomass	25	5.0	Cr (VI)	80%	Sheikhi and Rezaei (2021)
<i>Penicillium</i> sp.	Fungal Biomass	30	4.0	Cr (III)	75%	Sheikhi and Rezaei (2021)
<i>Cladonia rangiferina</i>	Lichen	25	2.0	Cr (VI)	92%	Pakade et al. (2019)
<i>Sphagnum squarrosum</i>	Moss	20	5.0	Cr (III)	75%	Pakade et al. (2019)
Moss (<i>Sphagnum</i> spp.)	Moss	25	4.0	Cr (VI)	85.5%	Kabdaşlı and Tünay (2023)
Lichen (<i>Cladonia</i> spp.)	Lichen	28	6.0	Cr (III)	88.7%	Kabdaşlı and Tünay, (2023)
<i>Saccharomyces cerevisiae</i>	Dead yeast cells	25	4.0	Cr (VI)	85.4%	Saini et al. (2023)
<i>Candida utilis</i>	Live yeast	30	5.5	Cr (III)	92.3%	Saini et al. (2023)
<i>Saccharomyces cerevisiae</i>	Yeast cells	25	2.0	Cr (VI)	83.5%	Acharyya et al. (2023)
<i>Saccharomyces cerevisiae</i>	Immobilized yeast	30	4.0	Cr (III)	78.2%	Arrisujaya et al. (2023)
<i>Kluyveromyces marxianus</i>	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 and Patil (2021)
<i>Prosopis spicigera</i>	Plant	-	2.0	Cr (VI)	97.69 %	Fernández et al. (2018)
<i>Sargassum dentifolium</i>	Plant	50	7.0	Cr (VI)	99.68%	Husien et al. (2019)

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⁻¹, the mining industry is 0.02-2.5 mg.L⁻¹, and the oil industry is 125-150 mg.L⁻¹ (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. PbSO₄, 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 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, is shown in Table 4.

Biosorption of Mercury (Hg)

According to USEPA, Mercury is a ubiquitous contaminant, a global pollutant that is highly toxic and is readily gathered in the 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 et al. 2022).

It's salts, such as mercurous and mercuric salts, attack the gut lining and the kidneys. According to the 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's 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 et al. 2020). Mercury pollution also originates from human activities, such as agriculture, battery

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 ⁻¹]	Reference(s)
<i>Bacillus licheniformis</i>	Bacteria	30	6.0	98%	Wen et al. (2018)
<i>Pseudomonas azotoformans</i>	Bacteria	30	6.0	88.58%	Choińska-Pulit, Sobolczyk-Bednarek and Łaba, (2018)
<i>Pannonibacter phragmitetus</i>	Bacteria	30	6.0	49.79 mg.g ⁻¹	Saravanan et al. (2021)RBTB
<i>Ralstonia solanacearum</i>	Bacteria	35	6.0	90%	Pugazhendhi et al. (2018)
Mixed- culture of algae	Algae	25 ± 2	6.0	95.43%	Mousavi et al. (2019)
<i>Sargassum muticum</i>	Algae	25	5.0	76 mg.g ⁻¹	Hannachi & Hafidh, (2020)
<i>Cladophora</i>	Algae	-	4.0	20.56 mg.g ⁻¹	Amro & Abhary (2019)
<i>Talaromyces islandicus</i>	Fungi	30	5.0	90.06%	Sharma et al. (2020)
<i>Rhizopus arrhizus</i>	Fungi	25	4.0	103.70 mg.g ⁻¹	Senol et al. (2021)
Filamentous fungus	Fungi	28	5.0	53.7%	Wang et al. (2019a)
<i>Phanerochaete chrysosporium</i>	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)
<i>Arundinaria alpina</i>	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)
<i>Phytolacca americana</i> L.	Plant Material	25	6.0	93.29%	Wang et al. (2018)
Banana Peels	Plant Material	-	5.0	98.14 %	Afolabi et al. (2021)

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 ⁻¹]	Reference(s)
<i>Pseudomonas putida</i>	Bacteria	30	8.0	99.72%	Zhao et al. (2021)
<i>Klebsiella</i> sp. NT8 and <i>Bacillus</i> sp. NT10	Bacteria	25	6.0	2597.62, 2617.23 mg.g ⁻¹	Xia et al. (2020)
Live or dead biomass of <i>A. marina</i> SSS2	Bacteria	35	7.0	87%, 95%	Mukkata et al. (2019)
<i>Chlorella vulgaris</i>	Algae	35	6.0	95.5%	Kumar et al., (2020)
<i>Ulva intestinalis</i> , <i>Ulva lactuca</i> , <i>Fucus spiralis</i> , <i>Fucus vesiculosus</i> , <i>Gracilaria</i> sp., <i>Osmundea pinnatifida</i>	Algae	Room Temp.	8.5	87.2%, 94.0%, 88.0%, 93.0%, 86.0%, 87.7%	Fabre et al. (2020)
<i>Ulva lactuca</i> Linnaeus	Algae	22.2	4.0	96.1% ± 0.7	Çetintaş et al. (2022)
<i>Sargassum crassifolium</i>	Algae	Room Temp.	9.0	98%	Putri and Syafiqa, (2019)
<i>F. velutipes</i>	Fungi	Room Temp.	7.0	69.35%	Li et al. (2018)
<i>Saccharomyces cerevisiae</i>	Fungi	25	5.4	89%	Hadiani et al.(2018)
<i>Penicillium</i> sp.	Fungi	60	4–5.0	99.6%	Sánchez-Castellón et al. (2022)
<i>Saccharomyces cerevisiae</i>	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 ⁻¹	Johs et al. 2019)
Coffee waste	Plant material	33	7.00	97%	Mora Alvarez et al. (2018)
<i>Thymus schimperi</i>	Plant material	25	7.0	90%	Geneti et al. (2022)

manufacturing, burning fossil fuels, mining and metallurgical processes, paint and chloralkali 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⁻¹ (Rani et al. 2021). According to research on biosorption, the hydrocolloid Gum Karaya had a maximum biosorption capacity of 62.5 mg.g⁻¹ 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⁻¹ of Hg²⁺ at 4.5 pH and 329 mg.g⁻¹ at 6 pH. In batch mode, it was found that lichen biomass (*Xanthoparmelia conspersa*) removed 82.8 mg.L⁻¹ of Hg²⁺ ions. In laboratory settings, *Pseudomonas aeruginosa* was found to exhibit a Hg²⁺ bioremediation capability of 62% (Tanwer et al. 2022). The different biosorption capacity of different biosorbents for the removal of Mercury ions from aqueous media is given in Table 5.

Fig. 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.

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.

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 particle sizes improve the ratio of surface

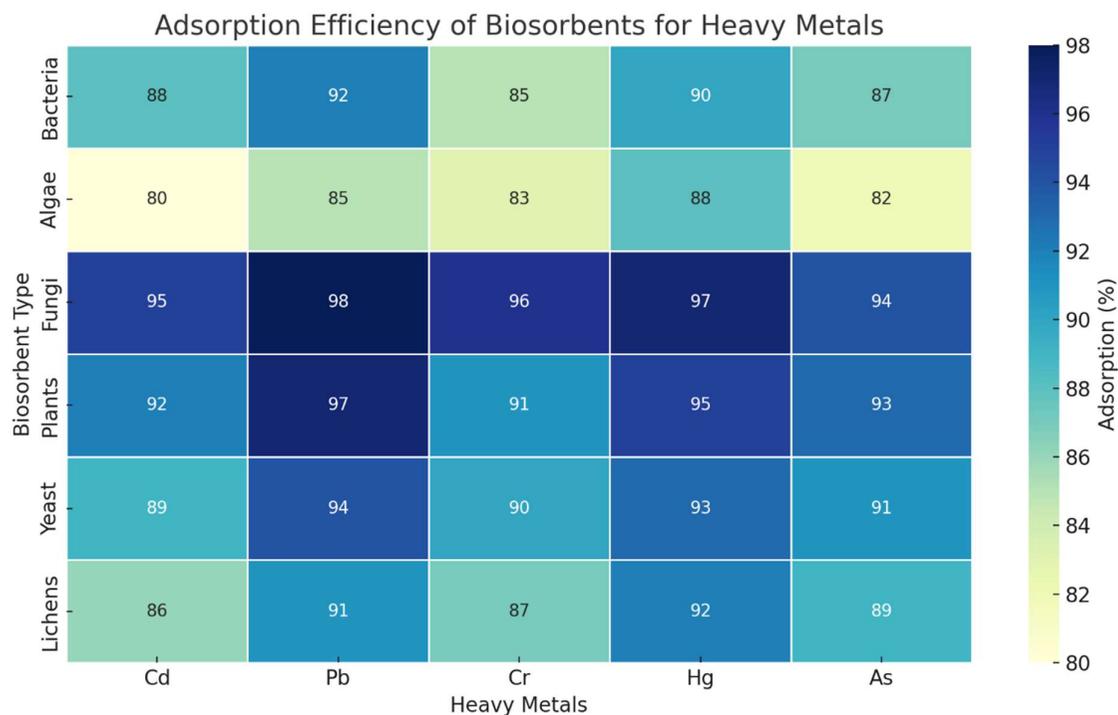


Fig. 7: Heavy metals adsorption by different biosorbents.

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 and 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 ⁻¹	Avanzi et al. (2014), Ali Redha (2020)
Initial Metal Concentration	Determines saturation level and helps assess biosorbent capacity	5–200 mg.L ⁻¹	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)

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 the interaction between metal and biomass, but must 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 times higher biosorption capacity for Pb²⁺, Cd²⁺, and Ni²⁺ ions as

compared to untreated material, demonstrating strongly the efficacy of modifying surfaces to improve metal capture in orange peel.

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 (Bayuo 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:

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

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.

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

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

Heavy Metal	Type of adsorbent	Desorbing agent	Desorption [%]	Reuse cycle	Reference(s)
Cr(VI), Pb(II)	Groundnut husk	HCl and H ₂ SO ₄	76.1, 82.1	5	Bayuo et al. (2020)
Pb(II)	Magnetic bentonite (M-B)	1.00 mol.L ⁻¹ 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	0.1 mol.L ⁻¹ HCl, 0.1 mol.L ⁻¹ 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, Bartzak and Jesionowski, (2016)
Pb(II)	Brown macroalga Sargassum ilicifolium	0.2 M HCl	88.0	3	Tabaraki et al. (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)

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 examine how lab results are applied to real contaminated water samples (Nathan et al. 2022).

For instance, it would not be easy to maximise 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 are 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, many 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 variable. 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.

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