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Fungi-Mediated Biosorption for Heavy Metal Removal

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Abstract: Toxic metal-contaminated industrial wastewater poses a serious risk to the environment and human health that calls for efficient cleanup techniques. This thorough analysis looks at biosorption as a viable, affordable substitute for traditional heavy metal removal techniques. In contrast to conventional methods like chemical precipitation, ion exchange, and membrane filtration, biosorption uses biological materials' ability to bind metals, such as bacteria, fungus, and biomass from agricultural waste, to remove contaminants from aqueous solutions. By highlighting both metabolism-dependent and metabolism-independent routes that allow metal ion removal through chelation, adsorption, precipitation, and complexation, the study summarizes the state of the art regarding biosorption mechanisms. Fungal biosorbents, which exhibit better performance because of their cell wall composition rich in chitin, polysaccharides, and functional groups that improve metal affinity, get special attention. Important operational variables, such as temperature, pH, biomass content, and metal ion concentration—that affect the effectiveness of biosorption are examined. In order to address metal contamination in industrial wastewater and support larger environmental restoration initiatives, this work highlights the significant benefits of biological remediation, such as economic viability, sustainability, minimal sludge generation, and regenerability of biosorbents.

Keywords: *Heavy Metal, Pollution, Bioremediation, Biosorption, Fungi, Fungal Biosorption.*

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I. INTRODUCTION

Heavy metal pollution has emerged as one of the most pressing environmental issues of the twenty-first century. Rapid industrialization, urbanization, mining activities, electroplating businesses, tannery operations, battery production, and agricultural practices have all contributed to the discharge of harmful heavy metals into soil and water environments [1]. Unlike organic contaminants, heavy metals are non-biodegradable, persistent, and may accumulate in living organisms, creating long-term environmental and public health problems [2].

Heavy metals, including lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), and nickel (Ni), are particularly hazardous due to their toxicity, even at low quantities. These metals enter the food chain through bioaccumulation and biomagnification, eventually affecting higher trophic levels, including humans. Heavy metal exposure has been linked to neurological diseases, kidney dysfunction, carcinogenesis, developmental abnormalities, and immune system damage [3]. The World Health Organization (WHO) has specified safe levels of heavy metals in drinking water; nonetheless, industrial emissions routinely exceed these safe levels, particularly in low-income nations [4].

Table 1 Acceptable Limits for Heavy Metals in Drinking Water.

Heavy metal/ metalloid	**Atomic weight (u)**	**Who limits (mg/L)(a)**	**US-EPA limits (mg/L)(b)**	**BIS limits (mg/L)(c)**
Arsenic (As)	74.92	0.01	0.010	0.01
Lead (Pb)	207.2	0.01	0.015	0.01
Cadmium (Cd)	112.41	0.003	0.005	0.003
Mercury (Hg)	200.59	0.006	0.002	0.001
Chromium (Cr)	51.99	0.05	0.1	0.05
Nickel (Ni)	58.69	0.07	0.1	0.02

(a)Guidelines for drinking water quality: Fourth edition, incorporating the first Addendum. ISBN 978-92-4-154995-0. World Health Organization, 2017. (b)2018 Edition of the Drinking Water Standards and Health Advisories Tables, Office of Water, U.S. Environmental Protection Agency. (c)Bureau of Indian Standards (BIS) (Source: Indian Standard [IS 10])

Raising awareness of heavy metals in our sources is currently a major concern, primarily because a wide range of industries discharge metal-containing effluents into water bodies without providing adequate treatment. When heavy metals build up in sensitive tissues and are no longer broken down by the body, they become toxic. Adults are often exposed through industrial means [5] [6]. Certain environmental elements (soil, air, and water) and their interactions can give rise to heavy metals.

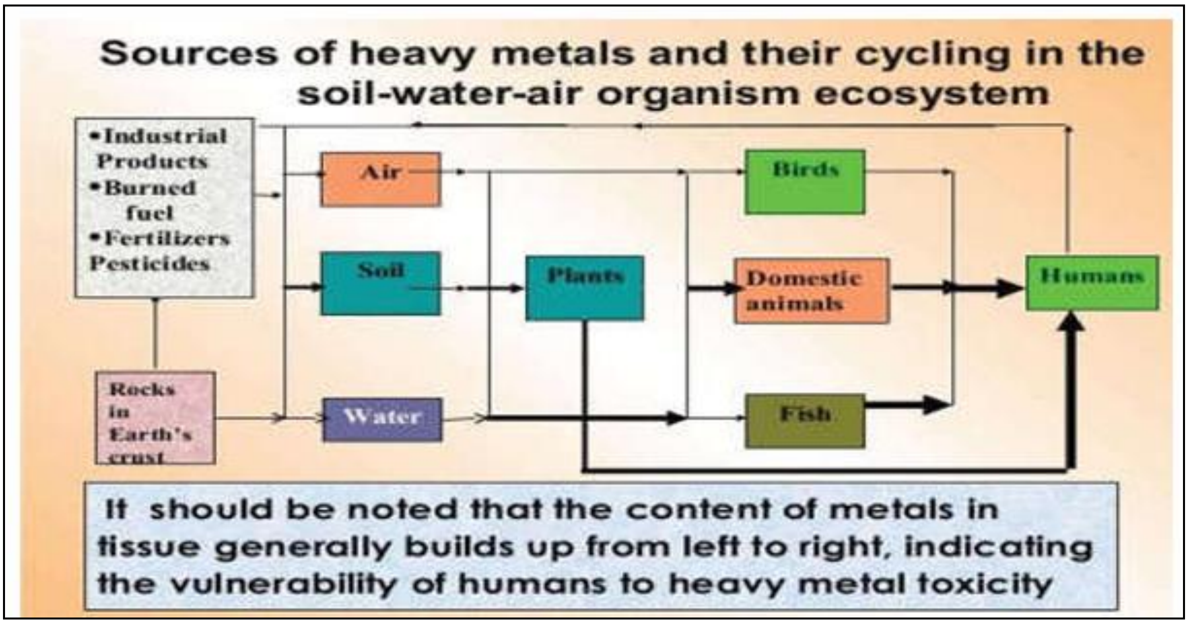

Fig 1 Sources of Heavy Metals with their Cycling in the Environment [7].

II. HEAVY METAL POLLUTION & ENVIRONMENTAL IMPACT

Numerous detrimental effects result from the environment's high concentration of heavy metals. All of the main environmental elements—the lithosphere, hydrosphere, biosphere, and atmosphere—are negatively impacted by these pollutants. Heavy metal contamination can cause major health issues, higher mortality rates, and significant disruption to food systems if not well controlled (Fig. 2) [8].

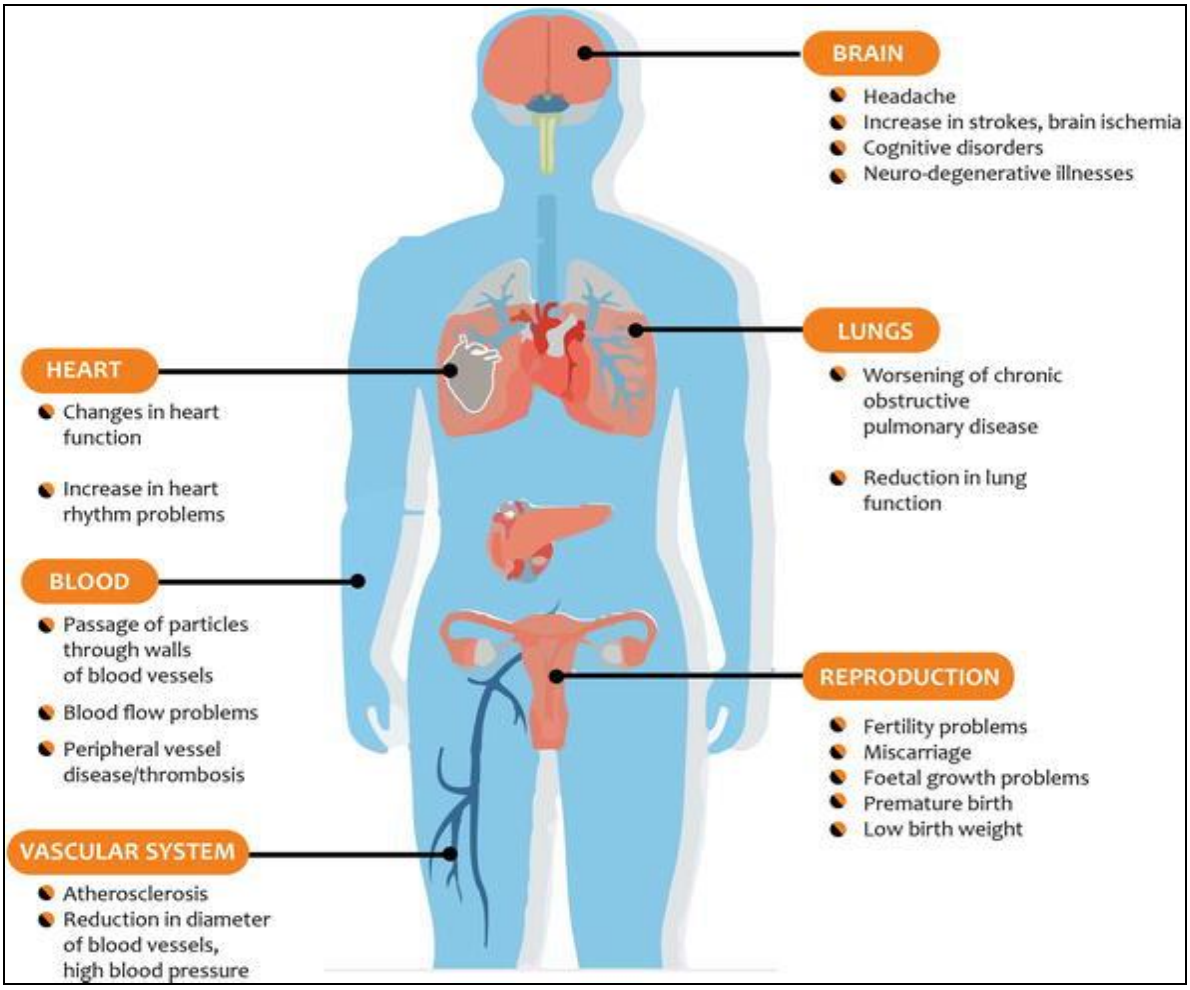

Fig 2 Effects of Heavy Metals on Different Vital Organs of Human Health [8].

Toxic metal ions seriously threaten both human health and the health of other organisms that exist. In extreme circumstances, these metals can result in life-threatening illnesses and irreparable harm to essential cellular systems. They can also induce physiological discomfort. The most dangerous heavy metals from an ecotoxicological aspect are mercury, lead, cadmium, and hexavalent chromium [Cr(VI)]. The particular impacts of heavy metals on human health are frequently unclear. Furthermore, environmental metal ions have a tendency to bioaccumulate in life forms and experience biomagnification throughout the food chain [9]. Because of biomagnification, the harmful effects of heavy metals become more noticeable in species at higher trophic levels. Under some circumstances, common metals like Cr(III), Cu, Zn, and Ni are thought to be less hazardous than metals like Fe and Al. However, chromium compounds are known to have nephrotoxic and carcinogenic qualities, especially in their toxic forms. Lead is extremely hazardous to humans and may seriously harm the kidneys, brain system, and reproductive system, particularly in young children. Long-term exposure to high cadmium levels has also been linked to hematological diseases, liver damage, bone deterioration, and renal failure. Lead and cadmium concentrations in drinking water are limited to 0.015 mg L^{-1} and 0.005 mg L^{-1}, respectively, according to the Environmental Protection Agency's (EPA) maximum allowable standards. Because of its prolonged biological half-life of around 10 to 30 years, which causes it to accumulate in the human body, cadmium is especially dangerous. Serious health consequences, including kidney damage, bone problems, and an elevated risk of cancer, can arise from long-term exposure to cadmium. Mercury exposure can cause nervous system disturbance, allergic skin responses, and negative reproductive outcomes. Additionally, it could reduce IQ and cognitive function [10], [11].

Numerous human activities, such as industrial processes, overuse of fertilizers, mining operations, disposal of metal-containing wastes, application of animal manure and sewage sludge, use of pesticides, wastewater irrigation, leaded fuels and paints, coal combustion residues, along with petrochemical spills, release heavy metals into the environment. These operations greatly increase heavy metal pollution of the soil. For heavy metals released into the environment by these sources, soils are regarded as important sinks. Additionally, the majority of heavy metals accumulate in the environment gradually due to their non-biodegradability and lack of microbial or chemical breakdown [12], [13].

Heavy metals are persistent and may destabilize entire ecosystems by entering food chains. Their presence in soil poses a serious environmental risk. Even though many organic pollutants are biodegradable, the presence of heavy metals often slows their degradation, worsening environmental contamination. Through a variety of pathways, including direct ingestion, uptake through the food chain, plant absorption, consumption of contaminated water, and changes in soil properties like pH, color, porosity, and natural chemical composition, heavy metals can endanger people, animals, plants, and ecosystems. These modifications eventually impact overall soil quality [14].

Air pollution is a major global environmental hazard due to the rapid urbanization and industrialization caused by the world's population expansion. Dust and particulate matter (PM), especially fine particles like PM2.5 and PM10, which are created by both natural and man-made activities, have significantly exacerbated air pollution. Dust storms, volcanic eruptions, soil erosion, and rock weathering are examples of natural sources of particulate matter, whereas industrial processes, mining, and transportation emissions are the main human sources [15].

The detrimental effects of particulate matter on the environment and human health make it a major source of concern. Numerous health problems, such as skin and eye irritation, early death, cardiovascular illnesses, and respiratory infections, can result from particulate matter exposure. Particulate pollution not only affects human health but also causes environmental issues such as corrosion, acid rain, eutrophication, and degradation of infrastructure, and haze, which reduces visibility [16]. Heavy metals are important constituents of particulate matter and may be generally divided into many classes. These comprise group I metals (such as Cd, Cu, and Pb), group II metals (such as Cr, Ni, V, and Zn), and group III metals (such as Na, K, Ca, Ti, Mg, Al, and Fe). These metals come from a variety of sources, such as natural processes, industrial processes, and vehicle emissions [17].

III. CONVENTIONAL TECHNIQUES FOR HEAVY METALLIC REMOVAL

Due to the release of substantial amounts of metal-contaminated wastewater from industrial operations, heavy metals, including nickel, copper, zinc, cadmium, chromium, lead, and mercury, are important environmental contaminants that have a substantial impact on freshwater systems. These metals build up in the environment, infiltrate the food chain, and cause major health problems since they are poisonous, persistent, and non-biodegradable. Heavy metals have been removed from polluted wastewater using several traditional treatment techniques during the past few decades. Chemical precipitation, ion exchange, membrane filtration, ultrafiltration, and reverse osmosis are often employed methods [18], [19], [20].

One of the most popular methods for eliminating heavy metals from inorganic wastewater is chemical precipitation. The fundamental process is the addition of chemical reagents (precipitants) that transform dissolved metal ions into insoluble forms. Metal hydroxides, carbonates, or phosphates are created as a result of this process and precipitate as solid particles. Sedimentation or filtering can then successfully remove these insoluble substances from the effluent.

The reversible exchange of ions between solid and liquid phases is the foundation of ion exchange. A solid resin that can exchange cations and anions from an electrolytic solution while also releasing an equal number of counter-ions with a comparable charge into the solution is known as an ion exchanger. This procedure allows dissolved metal ions to be effectively removed from wastewater while maintaining electrical neutrality.

Membrane filtration is a useful method for removing suspended particles, organic pollutants, and metal ions from wastewater. A membrane can have a porous or non-porous structure and serves as a selective barrier between two homogenous phases. Because of this selective feature, contaminants of different sizes may be eliminated via processes like size exclusion, diffusion, or electrostatic interactions.

The membrane-based separation method known as ultrafiltration (UF) makes use of membranes with pore diameters that normally fall between 0.1 and 0.001 µm. larger molecules, suspended particles, and colloids are retained, whereas water and low molecular weight solutes can flow through. Heavy metals, including Cu (II), Zn (II), Ni (II), and Mn (II), have been successfully removed from aqueous solutions using ultrafiltration, especially when combined with complexing agents like acrylic acid and malic acid copolymers [21].

In reverse osmosis (RO), a pressure-driven membrane separation technique, dissolved pollutants, including heavy metals, are extracted from wastewater by forcing a solution through a semipermeable membrane. This method is widely used for efficient purification in a variety of industrial applications. Metal ions, including Cu(II), Ni(II), and Zn(II), have been effectively removed by reverse osmosis employing polyamide thin-film composite membranes (such as TW30-1812-50) [22].

IV. BIOSORPTION

The hunt for more economical ways to treat wastewater polluted by metals began in the 1970s as environmental awareness and pollution concerns grew. As a result, alternative methods aimed at eliminating hazardous metals were developed. Among them, biosorption attracted a lot of interest since different biological materials have the ability to bind metals, making it a viable and affordable method of treating wastewater.

Research on biosorption has so far shown that it is a viable technique for decontaminating effluents that contain dyes and metals. Because they are made from waste or naturally existing biomass, biosorbents are especially beneficial because they are sustainable and affordable. Biosorption is a quick process in which non-living biomass or adsorbents passively sequester dyes or metal ions. According to studies, certain biosorbents exhibit binding capabilities that are similar to those of synthetic ion-exchange resins that are sold commercially [23].

The two primary stages of the biosorption process are a liquid phase, usually water, that contains the dissolved materials to be eliminated (adsorbates like metal ions or dyes), and a solid phase that contains the sorbent or biosorbent (biological material or adsorbent). These adsorbate species are drawn to and bonded to the surface by a number of physicochemical processes because of the biosorbent's strong attraction for them. The procedure is repeated until the concentration of adsorbate bonded to the solid phase and the residual concentration in the solution reach equilibrium.

Biosorbents can be made from a wide range of materials, such as biomass from freshwater and marine plankton, algae, fish, terrestrial plants, forests, and other living things. Together, these biological elements provide a sizable natural adsorbent pool. Biomass is a plentiful and sustainable source of a variety of chemical compounds suitable for biosorption applications, as it is renewable and can be grown either directly or indirectly through solar energy.

➢ *Significance of Biosorption*

Among the many noteworthy benefits of bioremediation are its great efficacy in detoxifying diluted effluents, low operating costs, and minimum production of waste sludge. It also enables in situ remediation, making it a viable and sustainable method for addressing polluted settings [24], [25]. Heavy metals can be detoxified by bacteria in a number of ways [26]. Cadmium (Cd) detoxification is mostly linked to efflux systems, despite the fact that several tolerance mechanisms have been found in microorganisms under heavy metal stress. Among the best understood processes are the CZC (cobalt–zinc–cadmium) transport system in *Alcaligenes eutrophus* and the plasmid-encoded cadmium resistance (CAD) systems in *Staphylococcus aureus*. By aggressively removing Cd ions from the intracellular environment, these mechanisms stop the harmful effects. Additionally, research has shown that compared to resistant strains, sensitive microbial strains can collect 4–15 times more cadmium [27]. The capacity of cadmium (Cd) ions to form covalent connections with sulfhydryl (-SH) groups is a crucial feature. Although this characteristic adds to their high toxicity, many species use it as a detoxifying tactic. Cadmium is sequestered and becomes less bioavailable inside the cell via interacting with metal-detoxifying ligands. Furthermore, both metabolism-dependent and metabolism-independent processes can bind heavy metal ions to the bacterial cell wall, especially peptidoglycan [28].

➢ *Metabolism-Based Biosorption*

Living biological systems use a variety of processes, such as chelation, adsorption, precipitation, and complexation, to carry out metabolism-dependent biosorption. A particular mechanism known as chelation occurs when metal ions make two or more coordinating bonds with a central metal atom to connect with polydentate ligands. Ions, atoms, or molecules from a liquid, gas, or dissolved solid adhere to a surface during adsorption, creating a thin layer of adsorbate on the adsorbent. Physisorption, which includes weak van der Waals forces, or chemisorption, which involves stronger covalent bonding, can cause this surface phenomenon; electrostatic interactions may also play a role [29]. Another method is precipitation, which is the formation of insoluble solid substances by diffusion or chemical reactions inside a solid matrix or within a solution. A precipitate is the solid that forms, and the precipitating agent is the chemical that causes it to form. Coordination complexes, in which a central metal ion (coordination center) combines with nearby molecules or ions referred to as ligands or complexing agents, are the result of complexation. Transition metals exhibit this phenomenon more frequently. Depending on the characteristics of the biosorbent and the surrounding circumstances, biosorption may use one or more of these pathways [30], [31]. ATP is needed when metal attachment to the cell wall is metabolism-dependent. Carboxyl, carbonyl, phosphoryl, hydroxyl, and sulfhydryl groups are functional groups found on the cell surfaces of biological materials that are essential for immobilizing metal ions before they are absorbed by the cell [31]. Additionally, metal absorption by living biomass is influenced by a number of parameters, such as the kind of metal ions, the environment, and the cell wall's composition [32]. The uptake process in living biomass involves the initial adsorption of metal ions onto the cell surface, followed by their transport into the cytoplasm [33], [34], [35].

- *Metabolism-Independent Biosorption*

The metabolism-independent process usually takes place in biomass made up of dead, non-living cells [36]. The adsorption process, which may include both physicochemical adsorption and ionic interactions, is the main factor controlling the physicochemical biosorption mechanism. Metal binding and biosorption are significantly influenced by functional groups found on the bacterial cell wall, including carboxyl, phosphate, amine, hydroxyl, and sulfhydryl groups. Because it can maintain ongoing metal absorption and self-regeneration under ideal circumstances, living biomass is frequently favoured over non-living biomass [34], [37]. Adsorption is a rapid process, whereas intracellular accumulation is energy-dependent and occurs more slowly [34], [33]. Depending on the physiological traits of the microbe, the fate of metals in microbial cells may entail accumulation, detoxification, or efflux pathways [37], [38]. Heavy metal-resistant bacteria have been the subject of much investigation in recent decades due to their potential utility in bioremediation. According to several studies, bacteria, including *Corynebacterium glutamicum*, *Pseudomonas*, and *Alcaligenes*, show considerable potential for detoxification and heavy metal removal, which makes them good candidates for bioremediation procedures [39], [37].

Heavy metals must first adsorb onto the cell surface or penetrate the cell in order to have physiological impacts on microbial development [40]. Microorganisms' metal absorption methods may be generally divided into two different systems. The first mechanism operates without the need for adenosine triphosphate (ATP) and is quick, non-specific, and constitutively active. The chemiosmotic gradient across the cytoplasmic membrane, which permits the passive transport of metal ions, is the main force behind this process. The second method, on the other hand, requires both the chemiosmotic gradient and metabolic energy in the form of ATP and is more selective, inducible, and slower. This active transport system typically appears when certain metabolic demands, nutritional deficiencies, or metal limitations are present. A critical precondition for later uptake and intracellular accumulation is the formation of metal–cell complexes as a result of the initial interaction between microbial cell surfaces and metal ions. Together, these pathways are essential for microbial metal homeostasis and detoxification [41]. Metal ions are carried into the periplasmic region of Gram-negative bacteria after initial surface sorption, and they then move into the cytoplasm. Microorganisms may acquire these ions intracellularly in the presence of high quantities of metal ions by a non-specific, quick, and constitutively active absorption mechanism that doesn't require ATP. Toxic metals can enter cells unintentionally due to this passive mechanism of transport. Due to their competition for binding sites with native metal cofactors, heavy metal ions can disrupt vital physiological processes. For example, Ni^{2+} and Co^{2+} may replace Fe^{2+}, Zn^{2+} may displace Mg^{2+} in enzymatic systems, and Cd^{2+} may compete with Zn^{2+} or Ca^{2+}. This kind of ionic interference causes metabolic abnormalities and interferes with regular cellular processes. Reactive oxygen species (ROS) production is a major effect of this disturbance, leading to oxidative stress and cellular damage. Heavy metal toxicity in microbiological systems is largely caused by oxidative stress [42].

V. BIOSORBENTS TYPES

Biosorbents fall into two general categories: biological materials that are living and those that are not. These groups vary in their practical applicability, efficiency, and metal absorption methods. Each category is described in depth below.

- *Non-Living Natural Materials*

Corn cobs, soybean hulls, cottonseed hulls, and different fruit peels are examples of agricultural and food sector wastes that are a plentiful and affordable supply of biosorbents. The main component of these by-products is lignocellulosic biomass, which is made up of cellulose, hemicellulose, and lignin. Functional groups, including hydroxyl, carboxyl, and phenolic groups, which are largely responsible for metal binding, are abundant in the cell wall components of these materials [43]. Cation exchange processes, in which metal ions in solution interact with negatively charged functional groups on the biosorbent surface, are primarily responsible for controlling the biosorption process. The metal ions and the functional groups create stable complexes as a result of this interaction, which makes it easier to remove them from aqueous environments. The type, accessibility, and affinity of these binding sites for specific metal ions determine the effectiveness of biosorption [44].

Among the most prevalent and adaptable microbes, bacteria make up a substantial amount of the Earth's total biological biomass, which is estimated to be around 10^{11} g. Bacteria typically have a very basic cellular arrangement despite their ecological variety. In terms of morphology, they are often divided into three main shapes: spiral forms (spirilla), rod-shaped forms (bacilli), and spherical or ovoid forms (cocci). However, because of genetic variety and environmental adaptations, bacterial form varies greatly.

Bacterial species range greatly in size in addition to form, which reflects their capacity to adapt to various ecological niches [45],[46]. Heavy metals are detoxified by bacteria using a variety of processes, such as extracellular sequestration, cell surface adsorption, and intracellular accumulation. The microbial cell wall's structure and composition, which include a variety of functional groups involved in metal binding, significantly influence how effective these activities are. The characteristics of these functional groups and the particular interaction processes at play determine the binding affinity and capability. The biosorption capability of several bacterial taxa, including *Bacillus*, *Pseudomonas*, *Desulfovibrio*, *Enterobacter cloacae*, and *Streptomyces*, has been thoroughly investigated. Through mechanisms including reduction, precipitation, or complexation, these bacteria may change poisonous metal ions into less dangerous forms and survive in a variety of environmental situations. Furthermore, by offering extra active sites, extracellular polymeric substances (EPS), especially polysaccharides released by bacteria, contribute significantly to metal binding. In contaminated settings, these extracellular elements also aid in the mineralization, immobilization, and degradation of pollutants.

Numerous microbes create iron-chelating substances, such as siderophores, which improve metal mobility and make it easier for heavy metals to be transformed and removed from polluted soils. Depending on the surroundings, these chelating compounds are essential for solubilizing metal ions and encouraging their absorption or immobilization. The bacterial cell wall, which is the main location for metal binding, is involved in the first stage of the biosorption process. Negatively charged functional groups, including carboxyl, phosphate, hydroxyl, sulfate, and amine groups, are abundant in the cell wall. Ion exchange, complexation, and electrostatic attraction are some of the ways that these functional groups interact with positively charged metal ions. Consequently, metal ions are efficiently adsorbed onto the cell surface, greatly enhancing the microorganisms' total capacity for biosorption [47], [26], [48].

Gram-negative bacteria often have a lesser ability for metal adsorption than Gram-positive bacteria, mainly because of variations in the structure of their cell walls. Gram-negative bacteria have more complicated cell envelopes made up of an outer membrane that contains proteins, phospholipids, lipoproteins, and lipopolysaccharides (LPS). By offering a variety of functional groups that can serve as ligands for metal ion binding, these components aid in the biosorption process and the cleanup of polluted areas.

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LPS in the outer membrane gives the cell surface an overall negative charge, which makes it easier for positively charged metal ions to be attracted to the cell surface. Through complexation processes and electrostatic interactions, phospholipids and functional groups like phosphate and carboxyl groups inside LPS operate as important metal ion binding sites. In contrast to Gram-positive bacteria, the structural arrangement of the outer membrane may restrict accessibility even while these binding sites allow metal absorption [49], [50].

- *Fungi*

Molds, yeasts, and mushrooms are examples of fungi, which are eukaryotic microorganisms that are widely found in a range of habitats. Their metabolism, structural structure, ecological flexibility, and genetic diversity are all very adaptable, allowing them to flourish in harsh and demanding environments. Because of these traits, fungi have been studied extensively for their potential to clean up environments polluted by heavy metals. Fungal systems can affect metal mobility by changing ion transport mechanisms and membrane permeability. Fungi are more effective in removing heavy metals than many unicellular microbes, partly because they may produce extracellular enzymes that breakdown substrates that would otherwise be insoluble. Low-grade ores, metal-bearing minerals, and industrial wastes are just a few of the matrices in which they may change metal. Fungi may also mobilize, immobilize, mineralize, and collect different metal ions and harmful elements, which helps in detoxification [29]. There are two main ways that fungi absorb heavy metals.

- The first is intracellular accumulation, also known as bioaccumulation, an energy-demanding, metabolism-dependent process.
- The second method is metabolism-independent biosorption, in which metal ions bind to the fungal cell wall by interacting physicochemically with surface functional groups.

Fungi are extremely efficient biosorbents for environmental remediation applications due to their coupled processes.

Both living and non-living fungal biomass have a considerable ability to absorb both useful and hazardous metal ions in the field of biosorption, indicating their potential as effective biosorbents in environmental remediation [34]. The distinct metabolic composition of the fungal cell wall confers a high affinity for metal binding. It is mainly composed of structural polymers such as chitin, glucans, and mannans, along with lipids, pigments (e.g., melanin), and other polysaccharides. Polysaccharides, which constitute 80–90% of the cell wall, provide numerous functional groups responsible for metal interaction. Metal ions bind to functional groups such as carboxyl, phosphate, hydroxyl, and amino groups, as well as uronic acids and nitrogen-containing ligands present in chitin and proteins. These interactions primarily occur through ion exchange, complexation, and electrostatic attraction, significantly enhancing the biosorption capacity of fungal biomass. Furthermore, physicochemical treatments such as autoclaving, heat treatment, and chemical modification using agents like formaldehyde, glutaraldehyde, orthophosphoric acid, sodium hydroxide (NaOH), and dimethyl sulfoxide (DMSO) can further improve biosorption efficiency by altering cell wall structure and increasing available binding sites [51]. *Trichoderma* spp., *Aspergillus* spp., *Rhizopus* spp., and *Penicillium* spp. are frequently employed as biosorbents. Glycoproteins with phosphate groups, which are essential for biosorption, are abundant in the cell wall components of these fungi. These phosphate groups become negatively charged at pH values above 3–4, thereby increasing their capacity to bind positively charged metal ions and making metal removal more efficient [36]. Metal ions in fungal cells attach to functional groups found in cell wall constituents such as chitin and chitosan, especially the amino groups ($-NH_2$ and -NH). Furthermore, carboxylate groups (pKa ~4–5) found in chitin-associated proteins play a major role in metal binding. Because of their reactive side chains, amino acid residues like glutamate, cysteine, and aspartate are also essential for metal chelation. The total biosorption capacity of fungal biomass is increased by these interactions [52], [53]. *Aspergillus niger* and *Ganoderma lucidum* are two examples of fungi that biosorb chromium through electrostatic interactions. The formation of a negative surface potential is facilitated by functional groups on the fungal cell wall, especially carboxyl and phosphodiester groups. This negative charge increases the effectiveness of biosorption by attracting and binding charged metal ions [54].

Table 2 Fungal Biosorbents for Heavy Metal Removal and their Source.

Metal(s)	Fungal Species	Source of Isolation	Reference
Pb	*Cunninghamella elegans* TUFC 20022; *Penicillium oxalicum*; *Penicillium chrysogenum*; *Penicillium digitatum*	Industrial wastewater	[55],[56], [57]
Co	*Paecilomyces* sp.; *Penicillium* sp.; *Aspergillus niger*	Polluted Air (industrial environment)	[52]
Cr, Pb, Cu, Al	*Fusarium* sp.; *Colletotrichum* sp.	Forest plants (*Shorea robusta*, *Terminalia bellerica*)	[58]
Ni	*Trichoderma* spp.	Soil	[59]
Cr	*Agaricus bisporus*; *Auricularia polytricha*	Not specified	[60]
Cu, Cd	*Penicillium funiculosum* LHL06	Crop plants in metal-contaminated agricultural soils	[61]
As	*Aspergillus flavus*; *Paecilomyces* sp.; *Aspergillus fumigatus*	Polluted air (industrial environment)	[62]
Zn, Pb	*Phoma*; *Alternaria*; *Peyronellaea* spp.	Rhizosphere of plants (*Arabis hirsuta*, *Acacia decurrens*, *Symplocos paniculata*)	[63]

VI. FACTORS AFFECTING BIO SORPTION

Numerous factors affect biosorption, which may be broadly classified into those due to the biosorbent (biomass), the characteristics of the metal ions, and the ambient circumstances. Together, these elements define the biosorption process's capacity and efficiency. The following are the main variables influencing biosorption:

- *Nature of Bio-Sorbents*

The type of biomass or derived product, such as freely suspended cells, immobilized preparations, active biofilms, etc., may also be considered one of the required components. While chemical treatments like alkali cure frequently increase biosorption capacity, physical treatments like boiling, drying, autoclaving, and mechanical disruption will all have an impact on binding homes. This is especially noticeable in some fungal structures because DE acetylation of chitin structures chitosan-glycan complexes with higher metal affinities [31]. The age of the biomass, growth conditions, and nutrient availability can all have a big impact on biosorption effectiveness. These variables change the availability and affinity of metal-binding sites by influencing cell size, cell wall composition, and extracellular material synthesis.

- *Concentration of Biomass*

The concentration of biomass has a major impact on the specific absorption of metal ions during biosorption; greater metal absorption per unit biomass is frequently observed at lower biomass densities, as opposed to greater densities at a fixed equilibrium metal concentration. Electrostatic interactions between cells, which intensify at higher biomass concentrations, are responsible for this occurrence. The availability of binding sites may decrease due to aggregation and overlap caused by an increase in biosorbent concentration. High biomass concentrations may therefore prevent metal ions from accessing active binding sites, which would reduce the biosorption efficiency per unit mass [23], [51].

- *pH*

One of the most important factors affecting the biosorption process is pH. It influences the competition between metal ions and protons for accessible binding sites, the ionization state of functional groups on the biosorbent surface, and the chemical speciation of metal ions. Numerous biological systems, including bacteria, cyanobacteria, algae, and fungi, have been shown to exhibit strong pH-dependent biosorption. Increased proton concentration at lower pH levels reduces the biosorption of metals including Cu, Cd, Ni, Co, and Zn by competing with metal cations for binding sites [62]. When the pH of the solution is lowered from 6.0 to 2.5, heavy metal absorption by the majority of biomass types generally declines dramatically. Due to intense proton competition for binding sites, metal elimination becomes insignificant or nonexistent at pH levels below 2.0. On the other hand, as pH rises from around 3.0 to 5.0, where ideal biosorption is usually seen, metal absorption increases. In order to achieve maximal metal sorption, it is also essential to maintain an optimum pH, as any rises beyond this range may result in a decrease in biosorption effectiveness.

➢ *Temperature*

The temperature range of 20–35 °C typically has little effect on biosorption efficiency, in contrast to bioaccumulation. Higher temperatures (e.g., about 50 °C) can sometimes improve biosorption, but they can also harm live microbial cells irreversibly, which eventually decreases metal absorption. Adsorption processes are usually exothermic since biosorption is mostly a surface phenomenon, and the degree of adsorption frequently rises with decreasing temperature [36].

➢ *Metal Ion Concentration*

According to [60] the initial metal concentration is essential to biosorption because it provides the force required to overcome the mass transfer barrier between the aqueous and solid phases. Because of increased interaction between metal ions and accessible binding sites, the amount of metal absorbed by the biomass increases as the initial concentration of metal ions rises. On the other hand, lower beginning concentrations usually result in a larger % removal of metals. Therefore, metal absorption rises with increasing starting metal concentration at a fixed biomass content, albeit removal efficiency may fall at higher concentrations [36].

VII. ADVANTAGES OF BIO SORPTION OVER CONVENTIONAL METHODS

➢ *Compared with Traditional Heavy Metal Removal Techniques, Biosorption Offers Several Benefits [31].*

- Economical because microbial biomass (fungi and bacteria) may be produced at a low cost.
- Effective use of biological materials to eliminate heavy metals.
- Capacity to concurrently adsorb many heavy metal ions.
- Adequate for handling substantial amounts of wastewater.
- High selectivity for particular metals results in little to no need for further chemical inputs.
- Effective in a variety of environmental settings, including pH, temperature, and the presence of competing ions.
- Makes it possible to desorb and recover adsorbed metals easily and affordably.
- Decreases the production of secondary pollutants and hazardous sludge.
- Sustainable and ecologically friendly remediation strategy

VIII. CONCLUSION

There is a demand for economic and ecologically friendly substitutes since traditional heavy metal removal techniques are frequently expensive and less sustainable. According to a significant amount of research, biosorption has become a cost-effective and environmentally responsible method for eliminating heavy metals from both residential and commercial wastewater. Because of its great efficiency, affordability, and decreased production of chemical or biological sludge, it is a prospective substitute for conventional treatment techniques.

The potential for metal recovery and biosorbent regeneration, quick adsorption–desorption kinetics, and efficient operation across a broad pH and temperature range are only a few benefits of biosorption. Biological biomass is also economically viable since it may be repurposed with little processing. The ability of biosorbents to remove metals is frequently on par with or even better than that of traditional adsorbents. Biosorption can enhance current treatment technologies rather than totally replace them, improving the process's overall sustainability and efficiency. As a result, biosorption is becoming more widely acknowledged as a useful and appealing method for heavy metal cleanup.

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