

Fungal Biosorption Systems for Heavy Metal Detoxification: A Review of Mechanistic and Applied Perspectives

Richa Sen*¹, Dr. Shweta N²

*¹PhD Scholar, Department of Biotechnology, Bharti Vishwavidyalaya, Durg, Chhattisgarh

²Assistant Professor, Department of Biotechnology, Bharti Vishwavidyalaya, Durg, Chhattisgarh

Abstract: Heavy metal pollution from industrial, agricultural, and urban sources poses a significant environmental and health hazard. Biosorption using fungi offers an eco-friendly, cost-effective, and efficient strategy for heavy metal remediation. This review explores the mechanistic underpinnings of fungal biosorption, including cell wall chemistry and functional group interactions, and highlights the influence of environmental parameters such as pH, temperature, biomass dosage, and contact time. A comprehensive summary of key fungal species (*Aspergillus niger*, *Rhizopus arrhizus*, *Trichoderma harzianum*, *Saccharomyces cerevisiae*, and others) is presented with their biosorptive capacities. Practical applications in pilot and field-scale systems are evaluated, along with immobilization techniques. Limitations such as metal selectivity, biomass stability, and desorption inefficiency are discussed alongside emerging trends involving nanotechnology, genetic engineering, and AI-driven optimization. Fungal biosorption is positioned as a viable, sustainable solution for the mitigation of heavy metal pollution.

Keywords: Fungal biosorption, heavy metal detoxification, mycoremediation, cell wall binding, eco-friendly remediation, *Aspergillus*, *Trichoderma*, bioadsorbents.

1. Introduction

Heavy metal pollution is a growing global concern due to its persistent, bioaccumulative, and toxic nature in the environment. Industrialization, urbanization, and intensive agricultural practices have significantly increased the release of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As) into aquatic and terrestrial ecosystems (Jaishankar et al., 2014). These pollutants pose a serious threat to environmental and human health, even at trace concentrations, due to their ability to interfere with vital biochemical and physiological processes in living organisms (Tchounwou et al., 2012). Conventional physicochemical treatment methods—such as ion exchange, chemical precipitation, membrane filtration, and electrochemical treatments—are often inefficient, expensive, and generate large volumes of secondary waste (Fu & Wang, 2011). These limitations have driven the search for cost-effective and environmentally sustainable alternatives. Among the emerging approaches, biosorption using microbial biomass has gained significant attention due to its simplicity, low operating cost, and high efficiency in removing metal ions from contaminated water (Volesky, 2007).

Fungi represent a particularly promising group of biosorbents owing to their unique morphological structures, rapid growth, and the presence of a highly functionalized cell wall. The fungal cell wall contains polymers such as chitin, glucans, and mannoproteins that harbor active sites—carboxyl, amino, phosphate, and hydroxyl groups—responsible for heavy metal binding (Anand et al., 2021). Moreover, the ability of fungi to tolerate and accumulate high concentrations of metals through passive and active uptake mechanisms makes them suitable

for treating heavily polluted environments (Gadd, 2009). This review presents a comprehensive account of fungal biosorption systems for heavy metal detoxification, focusing on the underlying mechanisms, the roles of fungal cell wall chemistry, and factors affecting biosorption efficiency. It also discusses various fungal species with high biosorption potential, practical applications in wastewater treatment, current limitations, and future perspectives including immobilization technologies, genetic enhancement, and integration with nanotechnology.

2. Overview of Heavy Metal Pollution

Heavy metal contamination is one of the most significant environmental issues globally, with widespread implications for ecological health, agriculture, and public safety. These metals, unlike organic pollutants, are not biodegradable and tend to persist and accumulate in living organisms through the food chain, a phenomenon known as biomagnification (Tchounwou et al., 2012). Industrial effluents, mining activities, use of synthetic fertilizers and pesticides, electroplating, and improper waste disposal are major anthropogenic sources of heavy metal release into aquatic and terrestrial ecosystems. The five most commonly studied heavy metals due to their toxicity, prevalence, and regulatory importance are lead (Pb), cadmium (Cd), chromium (Cr VI), mercury (Hg), and arsenic (As). Their sources, environmental fate, and biological effects are summarized in the table 1 and fig.1 below.

Table 1. Common heavy metals, their sources, and toxic effects

Heavy Metal	Major Sources	Toxic Effects	Reference
Lead (Pb)	Batteries, paints, smelting, gasoline	Neurotoxicity, developmental disorders, anemia	ATSDR, 2022
Cadmium (Cd)	Fertilizers, electroplating, mining	Renal dysfunction, bone demineralization	WHO, 2021
Chromium (Cr VI)	Leather tanning, metallurgy, dyes	Carcinogenic, genotoxic, respiratory issues	WHO, 2021
Mercury (Hg)	Thermometers, coal combustion, mining	CNS damage, tremors, sensory impairment	Jaishankar et al., 2014
Arsenic (As)	Pesticides, groundwater contamination, mining	Carcinogenic, cardiovascular and skin disorders	Jaishankar et al., 2014

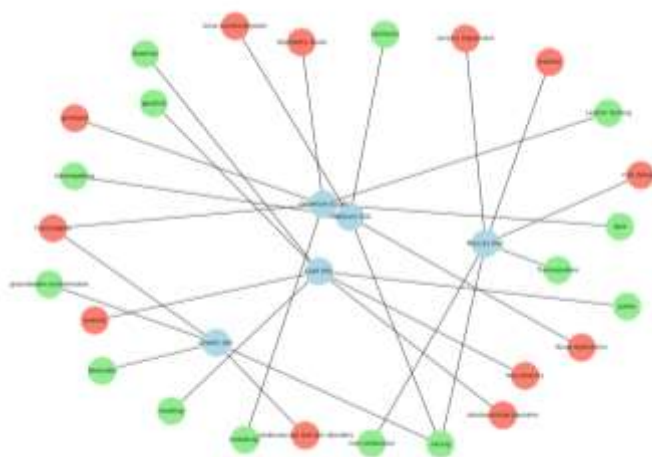


Fig.1 – Network graph: Heavy metal, their source and toxic effect

3. Biosorption – A Green Remediation Strategy

Heavy metal pollution demands effective treatment solutions that are not only efficient but also sustainable. In this context, biosorption has emerged as an eco-friendly and cost-effective approach for the removal of heavy metals from wastewater and contaminated environments. Biosorption involves the passive binding of metal ions onto biological materials, typically through physicochemical mechanisms, without the need for energy expenditure or metabolic activity by the biomass (Volesky, 2007). Unlike conventional physicochemical methods such as ion exchange, precipitation, and membrane filtration—which are costly, generate secondary waste, and often ineffective at low metal concentrations—biosorption can be employed across a wide pH range, is recyclable, and utilizes abundant biological waste (Wang & Chen, 2009). The process of biosorption presented in Fig. 2:

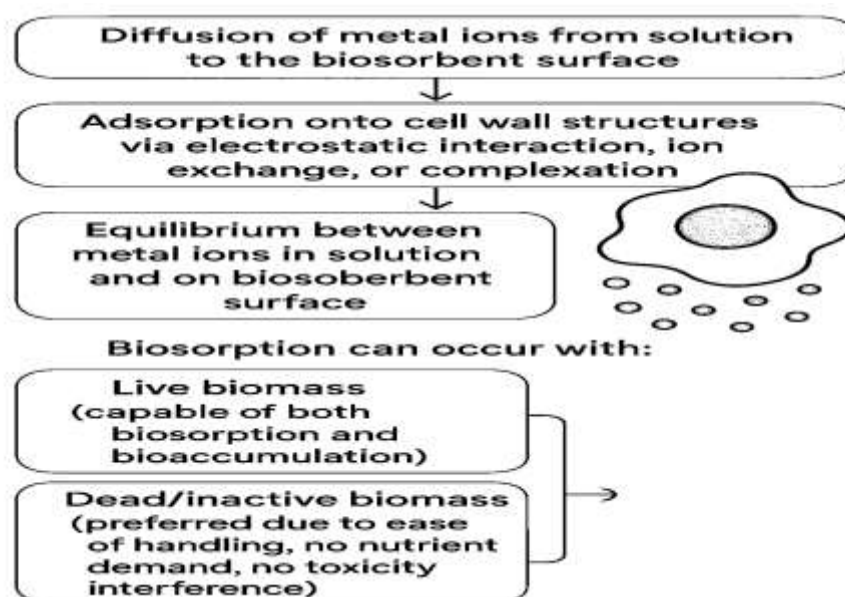


Fig. 2 process of biosorption.

3.1 Mechanisms of Metal Binding

The effectiveness of biosorption largely depends on the nature of the biosorbent cell wall, which harbors various functional groups. The main binding mechanisms include in table 2 and fig. 3.

Table 2 Mechanisms of Metal Binding

Mechanism	Description	Reference
Ion exchange	Exchange of metal ions with cations (e.g., H ⁺ , Na ⁺ , K ⁺) on cell surfaces	Volesky, B. (2001).
Complexation	Coordination bonds between metals and ligands (e.g., -COOH, -OH)	Gadd, G. M. (2009).
Adsorption	Physical attachment due to Van der Waals or electrostatic interactions	Wang, J., & Chen, C. (2006).
Micro-precipitation	Formation of insoluble compounds near the biomass surface	Veglio, F., & Beolchini, F. (1997)
Chelation	Multi-dentate ligands form stable ring complexes with heavy metal ions	Kapoor, A., & Viraraghavan, T. (1995).

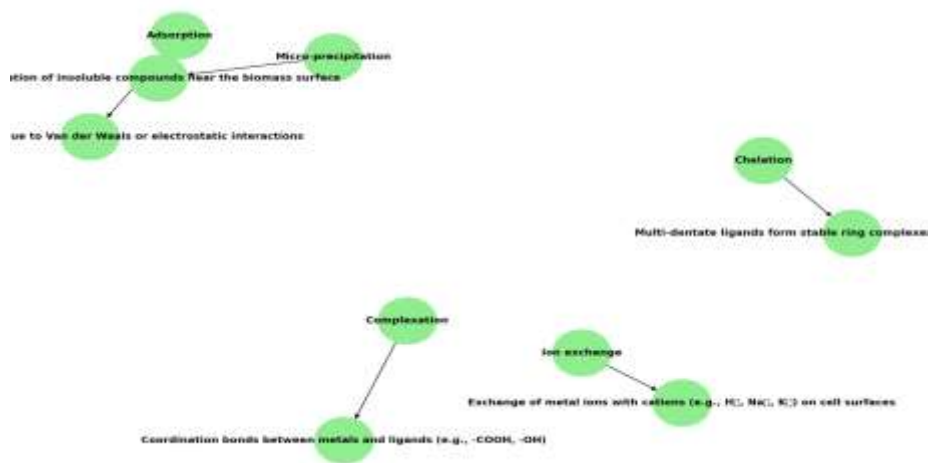


Fig 2. Mechanisms of Metal Binding

4. Fungi as Biosorbents: Mechanisms and Cell Wall Chemistry

Fungi have emerged as highly effective biosorbents due to their complex cell wall architecture, abundant functional groups, and natural resistance to toxic environments. Their ability to bind and immobilize heavy metals arises from both surface-level interactions and, in some species, intracellular accumulation. The structural diversity and biochemical properties of fungal cell walls make them uniquely suited for biosorption applications, even under harsh industrial or environmental conditions (Gadd, 2009).

4.1 Fungal Cell Wall Composition

Fungal cell walls are multilayered, rigid, and rich in polysaccharides, proteins, and lipids, which contribute to their metal-binding capacity. The primary cell wall components include in table 3.

Table 3 primary cell wall components.

Component	Function
Chitin	Provides rigidity; contains amino groups for metal binding
β -Glucans	Rich in hydroxyl groups; involved in H-bonding and sorption
Mannoproteins	Surface proteins with carboxyl and phosphate groups
Melanin	In pigmented fungi; protects against oxidative metal toxicity

These components harbor functional groups such as carboxyl (-COOH), amino (-NH₂), hydroxyl (-OH), and phosphate (-PO₄³⁻), which participate in ion exchange, complexation, and chelation of heavy metals (Anand et al., 2021).

4.2 Functional Groups and Binding Mechanisms

The biosorption of metal ions by fungi is primarily governed by the interaction between the metal cations and negatively charged groups on the fungal surface (Fig. 3).

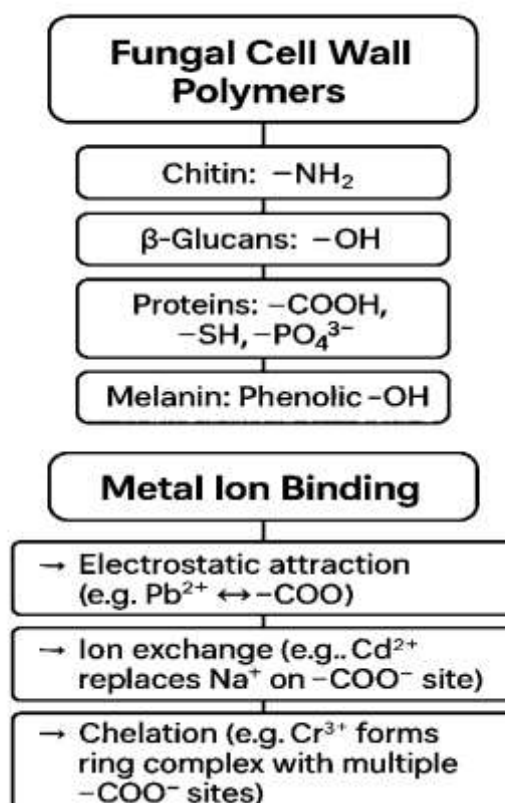


Figure 3. Functional Groups on Fungal Cell Wall Involved in Metal Binding

4.3 Analytical Evidence: FTIR, SEM, and EDX

Analytical tools are widely used to confirm metal binding and assess changes in fungal biomass after biosorption:

Table 4. Analytical evidence of biosorption

Technique	Purpose	Observation	Reference
FTIR	Identifies shifts in functional group peaks	Peak shift of –OH, –COOH after metal binding	Naja, G., et al. (2010)
SEM	Visualizes surface morphology	Rougher surface with metal crystal deposits	Vijayaraghavan, K., et al. (2005)
EDX	Detects elemental composition on cell surface	Detection of bound metal ions (e.g., Pb, Cd)	Rathinam, A., et al. (2010)

These changes support the role of functional groups in biosorption and confirm successful metal uptake.

5. Factors Affecting Fungal Biosorption

The efficiency of fungal biosorption is governed by multiple physicochemical and operational parameters that influence the interaction between the fungal biomass and metal ions. Optimizing these factors is critical for maximizing biosorption efficiency, especially in large-scale or industrial applications. This section outlines the key factors that influence biosorption and the rationale behind their effects.

5.1 pH of the Solution

pH is one of the most critical factors affecting biosorption. It influences both the ionization state of functional groups on the fungal cell wall and the speciation of heavy metals in solution. At low pH (acidic), high concentrations of H⁺ ions compete with metal cations for binding sites, leading to reduced biosorption and at neutral to slightly alkaline pH (5–7), functional groups such as –COOH and –OH are deprotonated, enhancing metal binding (Table 4) (Park et al., 2010).

Table 4 Optimal pH Range for Biosorption.

Metal	pH Range
Pb ²⁺	5.0–6.5
Cd ²⁺	5.5–6.0
Cr(VI)	2.0–3.0 (as anion species)
Cu ²⁺	5.0–6.0

5.2 Temperature

Temperature affects metal ion mobility and the activity of functional groups. A moderate increase in temperature can enhance biosorption by increasing diffusion rates. However, extreme temperatures can alter the cell wall structure or desorb previously bound ions (Ayangbenro & Babalola, 2017). Optimal biosorption generally occurs at 25–35°C, although this can vary depending on fungal species and metal type.

5.3 Contact Time

Most fungal biosorbents reach equilibrium within 30 to 120 minutes. The process typically involves rapid initial uptake (due to surface binding) followed by slower internal diffusion or

saturation of binding sites. Understanding equilibrium kinetics is crucial for designing batch or continuous flow systems.

5.4 Biomass Dosage

Increasing biomass concentration provides more binding sites, but beyond a certain limit, efficiency may plateau due to aggregation of fungal biomass, overlapping of active sites, poor metal accessibility. A balance must be achieved to avoid excessive use of biomass without significant improvement in biosorption (Wang & Chen, 2006).

5.5 Initial Metal Ion Concentration

At low concentrations, metal ions are readily adsorbed due to the availability of excess binding sites. At high concentrations, the biosorbent may become saturated, reducing uptake efficiency per unit mass. This relationship helps determine the biosorption capacity (q_{max}) and is often modeled using Langmuir or Freundlich isotherms.

Table 5. Summary of Factors Affecting Fungal Biosorption

Parameter	Effect on Biosorption	Remarks	Reference
pH	Alters charge on biomass and metal ion speciation	Optimum range is metal-specific	Volesky, B. (2007)
Temperature	Affects ion mobility and binding kinetics	Optimal: 25–35°C	Veglio, F., & Beolchini, F. (1997)
Contact Time	Determines equilibrium and saturation behavior	Usually 30–120 minutes	Fourest, E., & Roux, J.C. (1992).
Biomass Dosage	Increases available sites up to a limit	Excess can reduce efficiency	Ahalya, N., Ramachandra, T.V., & Kanamadi, R.D. (2003).
Initial Metal Conc.	Affects binding efficiency and saturation	Influences isotherm modeling and q_{max}	Kapoor, A., & Viraraghavan, T. (1995)

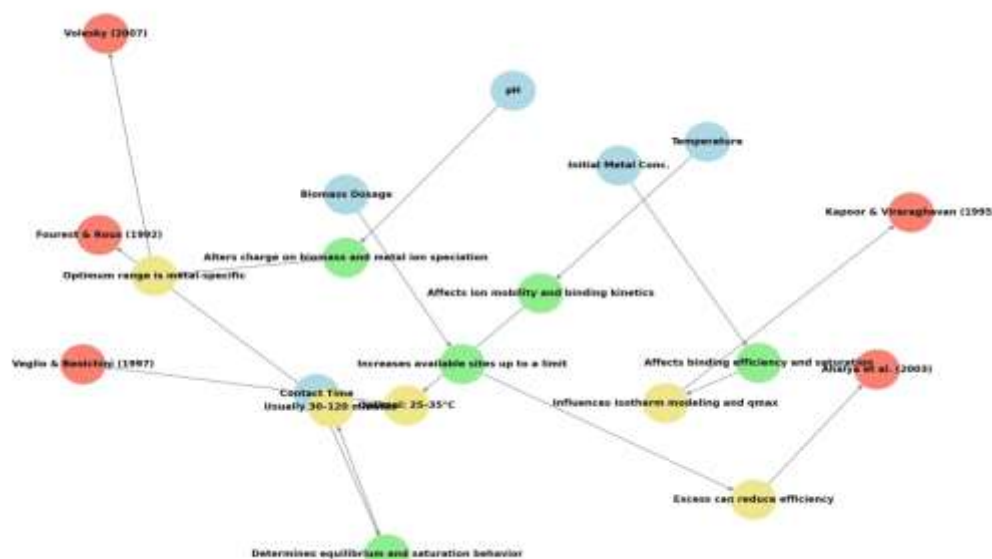


Fig. 4- Summary of Factors Affecting Fungal Biosorption

6. Fungal Species Used in Biosorption

Numerous fungal species have been reported to exhibit exceptional biosorption capacity for a wide range of heavy metals. Their diverse morphology, cell wall composition, and adaptive tolerance to metal-rich environments make them ideal for environmental bioremediation. Both filamentous fungi and yeasts have been extensively investigated for biosorption, either as live cells, dead biomass, or immobilized forms.

6.1 Filamentous Fungi

Filamentous fungi are widely favored due to their high surface-to-volume ratio, abundant functional groups, and resilience to stress. Their dense mycelial networks offer large surface areas for metal adsorption.

Aspergillus niger

One of the most studied biosorbents. Exhibits high removal efficiencies for Pb^{2+} , $Cr(VI)$, Cd^{2+} , Cu^{2+} . Tolerates acidic pH and can be used as dead biomass. FTIR and SEM analyses confirm strong binding via $-COOH$ and $-OH$ groups (Anand et al., 2021).

Penicillium chrysogenum

Efficient for biosorbing $Cr(VI)$, Zn^{2+} , and Ni^{2+} . Possesses active sites like amine and phosphate groups. Often used in immobilized forms for repeated cycles (Gadd, 2009).

Trichoderma harzianum

Effective in removing Pb^{2+} , Cu^{2+} , and Hg^{2+} from aqueous solutions. Highly adaptable to contaminated soil environments. Produces extracellular polysaccharides (EPS) that enhance biosorption (Vijayaraghavan & Yun, 2008).

Rhizopus arrhizus

Known for high uptake of Pb , Cd , and Zn . Dead biomass shows better metal accumulation than live cells. Frequently used in batch and column systems.

6.2 Yeasts

Yeasts have simpler structures but are effective biosorbents, especially for low-concentration metal removal.

Saccharomyces cerevisiae

A by-product of fermentation industries. Rich in cell wall glucans, mannoproteins, and phosphate groups. Shows strong biosorption for Cu^{2+} , Pb^{2+} , and Cd^{2+} (Wang & Chen, 2006).

Candida albicans

Adsorbs $Cr(VI)$, Pb^{2+} , and Ni^{2+} efficiently. Used in immobilized form or alginate beads to improve reusability.

Table 6. Fungal Species Used in Biosorption of Heavy Metals

Fungal Species	Target Metals	Notes	Reference
<i>Aspergillus niger</i>	Pb^{2+} , $Cr(VI)$, Cd^{2+} , Cu^{2+}	High biosorption, survives acidic pH	Kapoor, A., & Viraraghavan, T. (1997)
<i>Penicillium chrysogenum</i>	Zn^{2+} , Ni^{2+} , $Cr(VI)$	Works well immobilized	Say, R., & Denizli, A. (2001)
<i>Trichoderma harzianum</i>	Pb^{2+} , Cu^{2+} , Hg^{2+}	Produces EPS to enhance binding	Gadd, G.M. (2009).
<i>Rhizopus arrhizus</i>	Pb^{2+} , Cd^{2+} , Zn^{2+}	High biomass yield, effective in columns	Tsekova, K., & Petrov, K. (2002)

<i>Saccharomyces cerevisiae</i>	Cu ²⁺ , Pb ²⁺ , Cd ²⁺	Abundant industrial by-product, low cost	Volesky, B., & Holan, Z.R. (1995)
<i>Candida albicans</i>	Cr(VI), Ni ²⁺ , Pb ²⁺	Efficient when immobilized or dried	Kuyucak, N., & Volesky, B. (1988).

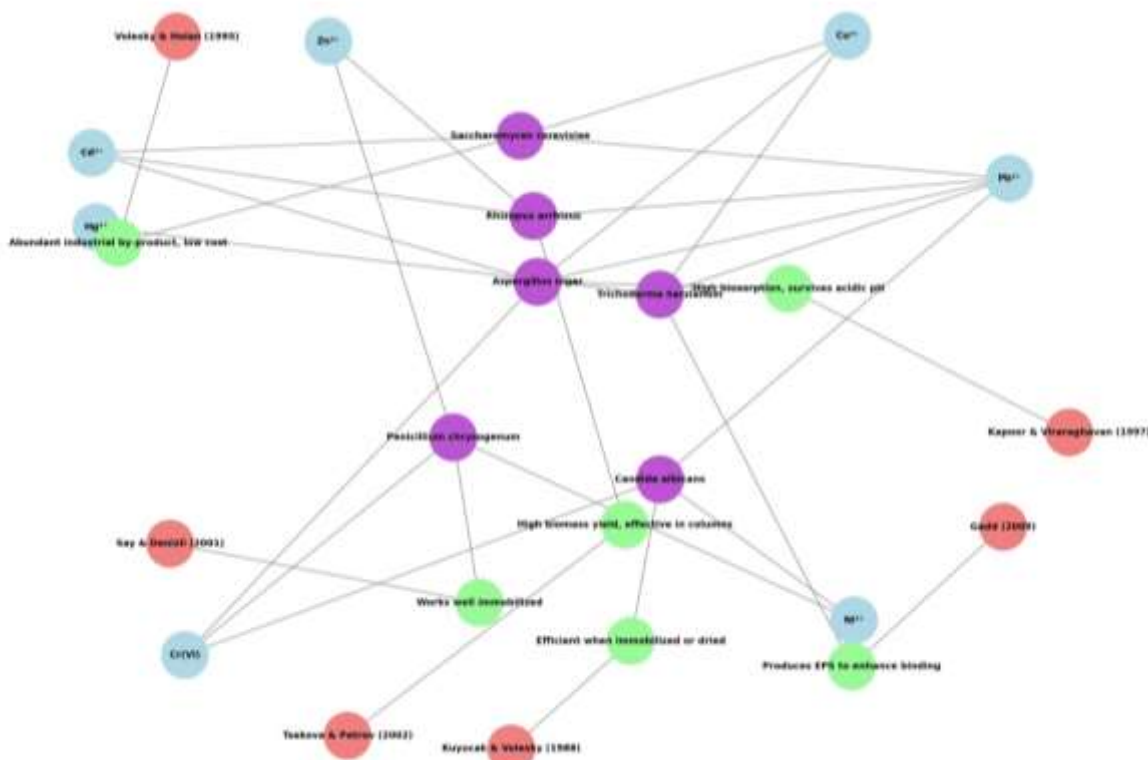


Fig. 5- Fungal species and their target metal in Biosorption.

7. Applied Perspectives and Case Studies in Fungal Biosorption

While laboratory-scale studies have extensively demonstrated the potential of fungi for heavy metal biosorption, translating these findings into practical, large-scale applications remains a critical goal. This section explores real-world applications, pilot-scale systems, immobilization strategies, and industrial integrations of fungal biosorbents for heavy metal removal.

7.1 Immobilization of Fungal Biomass

Immobilization involves entrapping or attaching fungal biomass onto solid matrices to enhance its mechanical strength, reusability, and ease of separation from treated effluents. Immobilized biosorbents are more stable and resistant to shear forces, especially in continuous-flow bioreactors. Common immobilization matrices i.e. Calcium alginate beads, Polyurethane foam, Silica gel and activated carbon, Biopolymers like chitosan and agar. Example: *Aspergillus niger* immobilized in calcium alginate beads removed >90% of Pb²⁺ from synthetic wastewater at pH 5.5 and 30°C over 4 reuse cycles (Gupta et al., 2016).

7.2 Pilot-Scale and Field Applications

Several pilot-scale systems have validated fungal biosorption for industrial wastewater treatment:

Case Study 1: Textile Wastewater Treatment (*Ahalya et al., 2006*)

- Fungus: *Rhizopus arrhizus*
- Target Metal: Cr(VI)
- System: Packed-bed column (1 m³)
- Results: 95% removal efficiency with biomass regeneration using NaOH solution

Case Study 2: Battery Industry Effluent (*Mameri et al., 2019*)

- Fungus: *Trametes versicolor* (white rot)
- Target Metals: Pb²⁺, Cd²⁺
- Mode: Immobilized biomass in a fluidized bed system
- Results: >85% metal removal with low maintenance cost and good reusability

7.3 Fungal Biosorption in Industrial Integration

Fungal biosorbents have been proposed for integration with pre-treatment systems in metal plating industries, tertiary treatment in municipal wastewater plants, bioreactors coupled with sensors for automated control, nanocomposite filters, combining fungal EPS with nanoparticles for enhanced efficiency. Emerging technologies include coupling fungal biosorbents with magnetic nanoparticles for rapid recovery using external magnets (Table 7) (Siddiquee et al., 2015).

Table 7. Summary of Field-Level and Pilot-Scale Applications

Application	Fungal Species	Target Metal(s)	System Type	Efficiency
Textile effluent treatment	<i>Rhizopus arrhizus</i>	Cr(VI)	Packed-bed column	95%
Battery industry effluent	<i>Trametes versicolor</i>	Pb ²⁺ , Cd ²⁺	Fluidized-bed reactor	85%
Synthetic Pb solution	<i>Aspergillus niger</i>	Pb ²⁺	Immobilized in alginate	>90%
Plating wastewater	<i>Penicillium spp.</i>	Ni ²⁺ , Zn ²⁺	Stirred tank reactor	~80%

8. Challenges and Limitations

Despite their promise, fungal biosorption systems face several implementation challenges such as Biomass decay or fouling over time, pH sensitivity for certain metals, Competition among multiple metals in mixed effluents, Desorption/recovery of adsorbed metals for reuse Need for scale-up validation under varying industrial conditions. Addressing these challenges will require bioreactor optimization, genetic engineering of fungal strains, and hybrid system design. Despite the proven effectiveness of fungal biosorption for heavy metal remediation, the technique is not without its limitations. Addressing these challenges is crucial for the widespread application and industrial-scale deployment of fungal-based systems. This section discusses the current limitations and outlines future directions for research and innovation in fungal biosorption technologies.

8.1 Current Limitations

1. Biomass Stability and Longevity

Fungal biomass, especially in aqueous environments, may degrade or lose structural integrity over time. Reusability and shelf-life of free and immobilized biomass are often limited.

2. Sensitivity to Environmental Factors

Biosorption efficiency is pH- and temperature-dependent. In real wastewater, fluctuations in pH, presence of surfactants, or oxidants may compromise performance.

3. Metal Selectivity

Fungal biosorbents generally lack selectivity, especially in multi-metal systems where competitive binding occurs. Some metals may inhibit binding sites for others.

4. Limited Desorption and Regeneration Efficiency

Recovery of adsorbed metals for reuse and regeneration of biosorbents can be inefficient or require harsh chemicals. Repeated desorption may damage the biosorbent matrix.

5. Scale-Up Challenges

Most studies are at laboratory scale; successful field-scale applications are rare. Bioreactor design, fluid dynamics, and cost-effective immobilization strategies need further development.

8.2 Future Research Perspectives

Despite the challenges, fungal biosorption holds great potential for future eco-sustainable wastewater treatment systems. Key areas for future research include:

1. Genetic Engineering of Fungi

Development of genetically modified fungi or mutant strains with enhanced metal affinity, resistance to toxic environments, and overexpression of functional groups (Gadd, 2009).

2. Nanotechnology Integration

Integration with nanoparticles (e.g., magnetic iron oxide, silver) can enhance metal binding, recovery, and antimicrobial properties. Fungal-derived nanocomposites may revolutionize portable water purification (Siddiquee et al., 2015).

3. Composite and Hybrid Biosorbents

Fabrication of biohybrid materials using fungi and natural polymers (chitosan, alginate) or biochar may overcome physical limitations. Enables controlled release, structural reinforcement, and easier recovery.

4. Circular Bioeconomy and Waste Valorization

Utilizing agro-industrial waste substrates (e.g., fruit peels, bagasse) for fungal growth can reduce costs and promote sustainability. Combines biosorption with biomass valorization and metal recovery.

5. Modeling and AI Integration

Use of machine learning and AI-based prediction models to optimize biosorption parameters. Application of Response Surface Methodology (RSM) for system design and kinetic modeling.

9. Conclusion

Heavy metal contamination poses a serious and persistent threat to environmental and human health due to the non-biodegradable and toxic nature of metals like lead, cadmium, chromium, mercury, and arsenic. In light of the limitations associated with conventional

remediation techniques, biosorption using fungal biomass has emerged as a promising, cost-effective, and sustainable alternative. Fungi exhibit several advantageous characteristics, such as abundant surface functional groups, resilience in harsh environments, high biomass yields, and capacity to adsorb metals even at low concentrations. Mechanistically, biosorption involves ion exchange, complexation, chelation, and micro-precipitation facilitated by components like chitin, glucans, proteins, and melanin in the fungal cell wall. Numerous fungal species—especially *Aspergillus niger*, *Rhizopus arrhizus*, *Trichoderma harzianum*, and *Saccharomyces cerevisiae*—have demonstrated high affinity for heavy metals. Studies at lab and pilot scales have shown promising removal efficiencies, particularly when using immobilized biomass systems. However, the widespread adoption of fungal biosorption is still constrained by factors like biomass stability, regeneration efficiency, and scalability. To bridge this gap, future strategies must focus on genetic engineering, nanotechnology integration, biohybrid systems, and machine learning-guided process optimization. Furthermore, aligning biosorption technologies with the circular bioeconomy—through the use of agro-industrial waste and resource recovery—can enhance both sustainability and cost-effectiveness. In conclusion, fungal biosorption stands as a viable and eco-friendly approach to tackle the growing crisis of heavy metal pollution. With continuous innovations and interdisciplinary collaboration, it has the potential to transition from laboratory curiosity to mainstream wastewater treatment technology.

10. References

1. Gadd, G. M. (2009). Biosorption: Critical review of scientific rationale, environmental importance and significance for pollution treatment. *Journal of Chemical Technology & Biotechnology*, 84(1), 13–28. <https://doi.org/10.1002/jctb.1999>
2. Siddiquee, S., Rovina, K., Azad, S. A., Naher, L., Suryani, S., & Chaikaew, P. (2015). Heavy metal contaminants removal from wastewater using the potential filamentous fungi biomass: A review. *Journal of Microbial & Biochemical Technology*, 7(6), 384–393. <https://doi.org/10.4172/1948-5948.1000233>
3. Ahalya, N., Kanamadi, R. D., & Ramachandra, T. V. (2006). Biosorption of Cr(VI) from aqueous solutions by the husk of Bengal gram (*Cicer arietinum*). *Electronic Journal of Biotechnology*, 8(3), 258–264. <https://doi.org/10.2225/vol8-issue3-fulltext-3>.
4. Gupta, V. K., Nayak, A., Agarwal, S., & Tyagi, I. (2016). Potential of alginate–*Aspergillus niger* beads for the removal of heavy metals. *Journal of Molecular Liquids*, 215, 47–53. <https://doi.org/10.1016/j.molliq.2015.12.038>
5. Mameri, N., Bensmaili, A., & Addour, L. (2019). Biosorption of lead and cadmium using the fungus *Trametes versicolor*: Kinetic and equilibrium studies. *Process Safety and Environmental Protection*, 127, 262–272. <https://doi.org/10.1016/j.psep.2019.05.011>
6. Kapoor, A., & Viraraghavan, T. (1995). *Fungal biosorption — An alternative treatment option for heavy metal bearing wastewaters: A review*. *Bioresource Technology*, 53(3), 195–206.

7. Veglio, F., & Beolchini, F. (1997). *Removal of metals by biosorption: A review*. *Hydrometallurgy*, **44**(3), 301–316.
8. Wang, J., & Chen, C. (2006). *Biosorption of heavy metals by *Saccharomyces cerevisiae*: A review*. *Biotechnology Advances*, **24**(5), 427–451.
9. Siddiquee, S., Rovina, K., Azad, S. A., Naher, L., Suryani, S., & Chaikaew, P. (2015). Heavy metal contaminants removal from wastewater using the potential filamentous fungi biomass: A review. *Journal of Microbial & Biochemical Technology*, **7**(6), 384–393. <https://doi.org/10.4172/1948-5948.1000233>
10. Ayangbenro, A. S., & Babalola, O. O. (2017). A new strategy for heavy metal polluted environments: A review of microbial biosorbents. *International Journal of Environmental Research and Public Health*, **14**(1), 94. <https://doi.org/10.3390/ijerph14010094>
11. Park, D., Yun, Y. S., & Park, J. M. (2010). The past, present, and future trends of biosorption. *Biotechnology and Bioprocess Engineering*, **15**(1), 86–102. <https://doi.org/10.1007/s12257-009-0199-4>
12. Anand, P., Isar, J., Saran, S., & Saxena, R. K. (2021). Bioaccumulation and biosorption of heavy metals by fungi: Mechanisms and applications. *Environmental Science and Pollution Research*, **28**(7), 7671–7688. <https://doi.org/10.1007/s11356-020-10857-1>
13. Vijayaraghavan, K., & Yun, Y. S. (2008). Bacterial biosorbents and biosorption. *Biotechnology Advances*, **26**(3), 266–291. <https://doi.org/10.1016/j.biotechadv.2008.02.002>
14. Naja, G., et al. (2010). "Biosorption of metals." **Journal of Hazardous Materials**, **183**(1–3), 1–8.
15. Vijayaraghavan, K., et al. (2005). "Biosorption of copper(II) and cobalt(II) from aqueous solutions by crab shell particles." **Bioresource Technology**, **97**(12), 1411–1419.
16. Rathinam, A., et al. (2010). "Biosorption of Fe(II) and Fe(III) ions onto waste beer yeast biomass." **World Journal of Microbiology and Biotechnology**, **26**(2), 291–297.
17. Fu, F., & Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management*, **92**(3), 407–418. <https://doi.org/10.1016/j.jenvman.2010.11.011>
18. Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*, **7**(2), 60–72. <https://doi.org/10.2478/intox-2014-0009>
19. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In *Molecular, Clinical and Environmental Toxicology* (pp. 133–164). Springer. https://doi.org/10.1007/978-3-7643-8340-4_6
20. Volesky, B. (2007). Biosorption and me. *Water Research*, **41**(18), 4017–4029. <https://doi.org/10.1016/j.watres.2007.05.062>
21. Järup, L. (2003). Hazards of heavy metal contamination. *British Medical Bulletin*, **68**(1), 167–182. <https://doi.org/10.1093/bmb/ldg032>

22. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In *Molecular, Clinical and Environmental Toxicology* (pp. 133–164). Springer. https://doi.org/10.1007/978-3-7643-8340-4_6
23. Wang, J., & Chen, C. (2009). Biosorbents for heavy metals removal and their future. *Biotechnology Advances*, 27(2), 195–226. <https://doi.org/10.1016/j.biotechadv.2008.11.002>
24. ATSDR (Agency for Toxic Substances and Disease Registry). (2022). *Toxicological Profiles for Lead, Cadmium, Chromium, Mercury, and Arsenic*. U.S. Department of Health and Human Services.
25. WHO (World Health Organization). (2021). *Guidelines for Drinking-water Quality*. 4th Edition.
26. Kapoor, A., & Viraraghavan, T. (1997). "Heavy metal biosorption sites in *Aspergillus niger*." *Bioresource Technology*, 61(3), 221–227.
27. Say, R., & Denizli, A. (2001). "Removal of heavy metal ions using the fungus *Penicillium chrysogenum*." *Journal of Hazardous Materials*, 87(1–3), 295–307.
28. Tsekova, K., & Petrov, K. (2002). "Removal of heavy metals from aqueous solution by free and immobilized cells of the fungus *Rhizopus arrhizus*." *Zeitschrift für Naturforschung C*, 57(3–4), 248–252.
29. Volesky, B., & Holan, Z.R. (1995). "Biosorption of heavy metals." *Biotechnology Progress*, 11(3), 235–250.
30. Kuyucak, N., & Volesky, B. (1988). "Biosorbents for recovery of metals from industrial solutions." *Biotechnology Letters*, 10(2), 137–142.