



Biosorption of Heavy Metals from Mine Tailing

Vivek Daharwal¹ and Ram Chandra Chaurasia²

¹ M.Tech Scholar, Department of Mining Engineering, Lakshmi Narain College of Technology, Jabalpur, Madhya Pradesh, 482053, India.

² Associate Professor, Department of Mining Engineering, Lakshmi Narain College of Technology, Jabalpur, Madhya Pradesh, 482053, India.

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Abstract

The rapid growth of industrialization, particularly since the mid-20th century, has led to a significant increase in the discharge of heavy metals into aquatic and terrestrial ecosystems. Mine tailings and industrial effluents serve as major sources of toxic metals such as lead, chromium, mercury, cadmium, arsenic, and nickel, which persist in the environment and pose severe risks to human health due to their carcinogenic, neurotoxic, and bioaccumulative nature. Conventional remediation techniques, including chemical precipitation and ion exchange, are often costly, inefficient at low concentrations, and may generate secondary pollutants, thereby necessitating the development of sustainable alternatives.

Biosorption has emerged as a promising, eco-friendly, and cost-effective approach for the removal of heavy metals from contaminated environments, including mine tailings. This process involves the passive binding of metal ions to biological materials such as bacteria, fungi, algae, yeasts, and agricultural residues, facilitated by functional groups like carboxyl, hydroxyl, and amino groups present on cell surfaces. Both living and non-living biomass exhibit biosorptive capabilities, making the process versatile and scalable. Key factors influencing biosorption efficiency include pH, temperature, initial metal concentration, biomass dosage, and surface characteristics of the biosorbent.

Microalgae-based biosorption, particularly using species such as *Chlorella vulgaris*, has demonstrated high efficiency in removing metal ions like Cu(II) and Co(II), following pseudo-second-order kinetics and fitting well with Langmuir and Freundlich isotherm models. Advances in bioremediation strategies, including immobilization techniques, biochar application, and microbial consortia development, further enhance metal removal efficiency and sustainability. Additionally, desorption and recovery of metals using suitable agents contribute to resource recovery and reuse.

This study highlights the mechanisms, influencing parameters, and modeling approaches associated with biosorption, emphasizing its potential as a sustainable solution for the remediation of heavy metal-contaminated mine tailings. It also identifies current limitations and research gaps, advocating for improved system design, large-scale implementation, and integration with advanced detection and monitoring technologies for effective environmental management.



Keywords: Biosorption; Heavy metals; Mine tailings; Microbial remediation; Sustainable treatment

1. Introduction

The rapid pace of industrialization, urbanization, and population growth over the past century has profoundly transformed natural ecosystems, resulting in widespread environmental degradation. Among the various pollutants released into the environment, heavy metals have gained significant attention due to their persistence, toxicity, and bioaccumulative nature. Unlike organic pollutants, heavy metals are non-biodegradable and can remain in the environment for extended periods, posing long-term ecological and health risks (Kumar et al., 2015; Jaishankar et al., 2014). These elements are naturally present in the Earth's crust; however, anthropogenic activities such as mining, smelting, industrial processing, and agricultural practices have drastically elevated their concentrations in soil, water, and air (Mitra et al., 2022).

Mining activities, in particular, represent a major source of heavy metal contamination. The extraction of valuable minerals from ores generates large quantities of waste materials known as mine tailings. These tailings typically consist of finely ground rock particles mixed with process water and residual chemicals used during extraction. Importantly, mine tailings often contain significant concentrations of toxic heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), mercury (Hg), nickel (Ni), copper (Cu), and zinc (Zn), which can be released into the environment through leaching processes (Suresh Kumar et al., 2015; Wang & Chen, 2009). With the increasing use of bioleaching techniques for metal extraction from low-grade ores and industrial wastes, the generation of metal-rich leachates has also increased (Rawlings et al., 2003; Johnson, 2014). These leachates require effective treatment prior to discharge to prevent contamination of surrounding ecosystems.

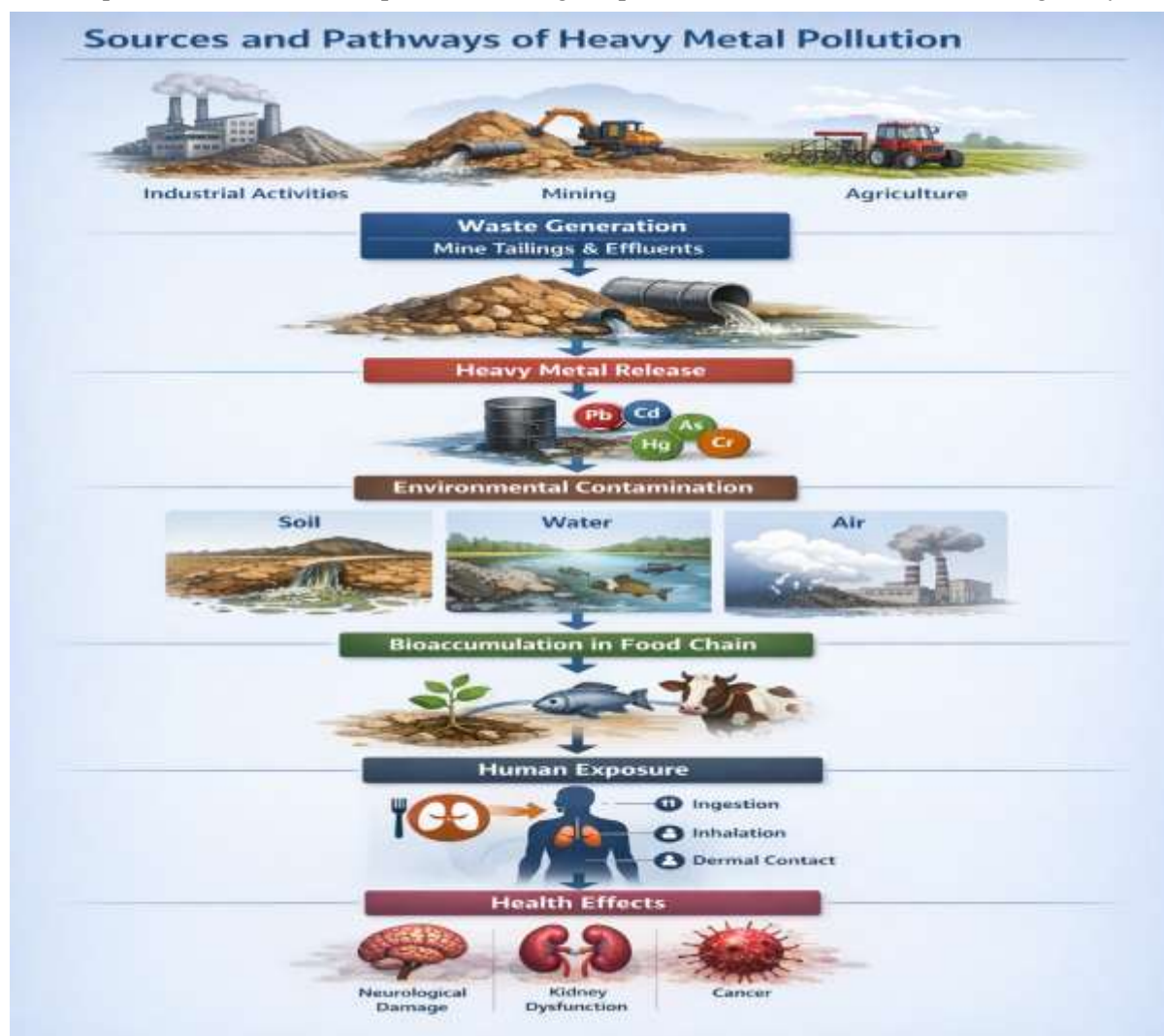


Figure 1 Source and pathway of heavy metals pollutions



Heavy metals are generally defined as metallic elements with high atomic weight and density greater than 4–5 g/cm³ (Shanab et al., 2012). They can be broadly classified into three categories: toxic metals (e.g., Pb, Cd, Hg, As), essential trace metals (e.g., Cu, Zn, Co), and radionuclides (e.g., uranium, thorium) (Wang & Chen, 2009). While essential metals play important roles in biological systems at trace concentrations, they become toxic when present in excess. In contrast, non-essential metals such as lead and mercury are harmful even at low concentrations and have no known beneficial biological function (Jaishankar et al., 2014). The toxicity of heavy metals arises from their ability to bind with proteins and nucleic acids, disrupt enzymatic activities, generate reactive oxygen species, and interfere with cellular metabolism (Liu et al., 2023).

The environmental distribution of heavy metals has become a global concern due to their widespread occurrence and persistence. Industrial sectors such as mining, electroplating, leather tanning, textile manufacturing, petroleum refining, and fertilizer production contribute significantly to heavy metal pollution (Hong et al., 2011; Karn et al., 2021). In addition to industrial sources, agricultural activities involving the use of fertilizers, pesticides, and sewage sludge also contribute to metal accumulation in soils and water bodies (Kumar et al., 2015). Improper disposal of industrial effluents and solid wastes, including mine tailings, further exacerbates the problem by facilitating the release of metals into aquatic and terrestrial ecosystems.

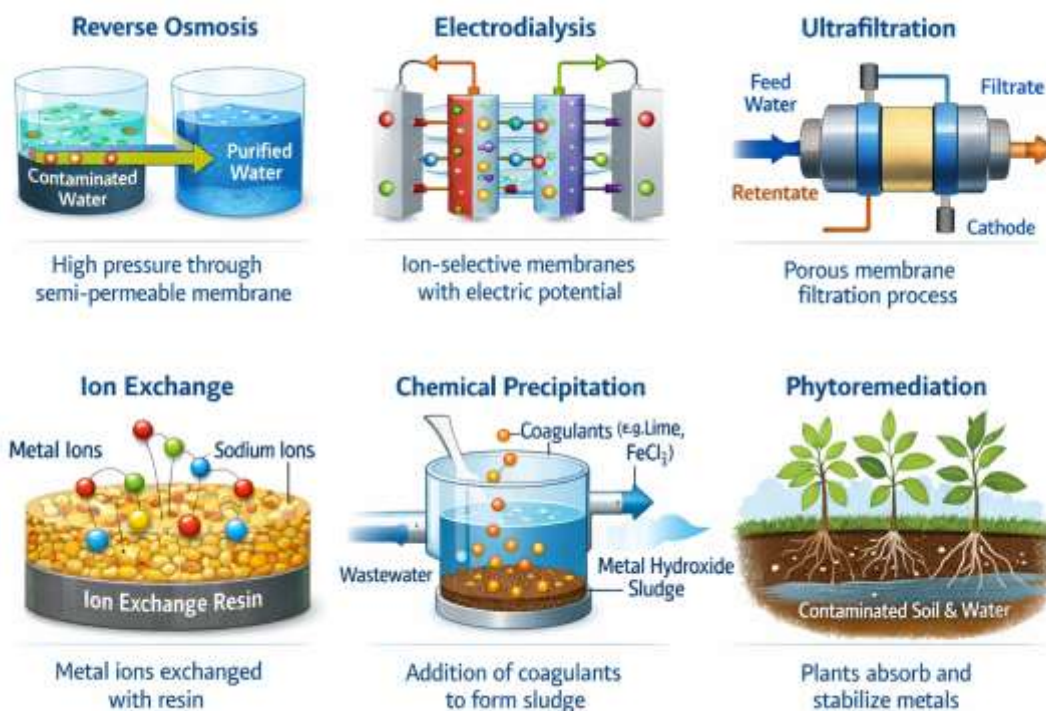


Figure 2 commonly used procedures for removing metal ions

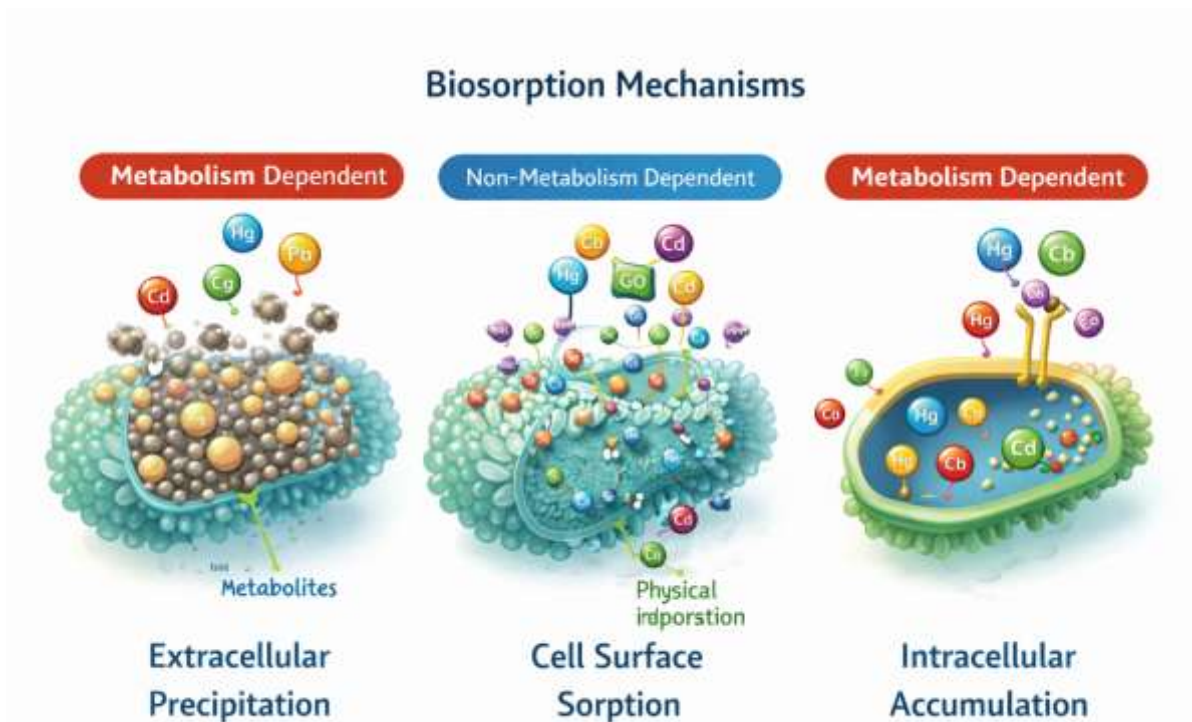
One of the most concerning characteristics of heavy metals is their ability to bioaccumulate and biomagnify through food chains. Once introduced into the environment, these metals can be taken up by plants, microorganisms, and aquatic organisms, eventually entering the human food chain (Anser et al., 2020). The accumulation of heavy metals in biological systems can lead to chronic toxicity, even when environmental concentrations are relatively low. This phenomenon poses serious risks to biodiversity, ecosystem stability, and human health.

The adverse effects of heavy metal exposure on human health are well documented. Neurological disorders, developmental abnormalities, kidney damage, cardiovascular diseases, respiratory issues, and various forms of cancer have been associated with heavy metal toxicity (Taylor et al., 2018; Yang et al., 2020). For instance, prolonged exposure to lead can result in cognitive impairment and behavioral disorders, particularly in children.



Mercury exposure affects the central nervous system, leading to neurotoxicity and motor dysfunction. Arsenic and cadmium are recognized carcinogens and have been linked to cancers of the skin, lungs, and kidneys (Liu et al., 2023). Furthermore, heavy metals can cause oxidative stress, DNA damage, and disruption of endocrine functions, thereby contributing to a wide range of chronic diseases.

Figure 3 Biosorption Mechanisms:



Given the severity of heavy metal pollution, considerable efforts have been made to develop effective remediation technologies. Conventional methods for heavy metal removal from wastewater and leachates include chemical precipitation, ion exchange, solvent extraction, membrane filtration, reverse osmosis, and adsorption (Razzak et al., 2022a). While these methods are widely used, they often suffer from several limitations. Chemical precipitation, for example, generates large volumes of sludge that require further treatment and disposal. Ion exchange and membrane filtration techniques are associated with high operational costs and require sophisticated infrastructure. Additionally, these methods may be ineffective for removing metals at low concentrations and may involve the use of hazardous chemicals (Shrestha et al., 2021).

In recent years, the limitations of conventional methods have prompted the exploration of alternative approaches that are more sustainable, cost-effective, and environmentally friendly. Biological methods, collectively referred to as bioremediation, have emerged as promising solutions for the removal of heavy metals from contaminated environments (Priya et al., 2022). Bioremediation utilizes the natural abilities of microorganisms, plants, and algae to remove, transform, or immobilize pollutants through various mechanisms such as biosorption, bioaccumulation, biotransformation, and biomineralization (Hassan et al., 2017).

Among these mechanisms, biosorption has gained considerable attention as an efficient and versatile technique for heavy metal removal. Biosorption is a physicochemical process in which metal ions are passively bound to the surface of biological materials, known as biosorbents (Volesky, 2007). Unlike bioaccumulation, which requires living cells and active metabolism, biosorption can occur using both living and non-living biomass. This characteristic makes biosorption particularly advantageous, as it allows for the use of waste biomass and eliminates the need for maintaining living cultures.



A wide variety of materials have been investigated as biosorbents, including bacteria, fungi, algae, yeasts, and agricultural residues such as rice husks, sawdust, and fruit peels (Gupta & Rastogi, 2008). The efficiency of biosorption depends largely on the presence of functional groups on the surface of the biosorbent. These functional groups, including carboxyl, hydroxyl, amino, and phosphate groups, interact with metal ions through mechanisms such as ion exchange, complexation, and electrostatic attraction (Volesky, 2007). The structure and composition of the cell wall play a crucial role in determining the biosorption capacity of the biomass.

Fungal biomass has been extensively studied as a biosorbent due to its high metal-binding capacity, low cost, and ease of cultivation. Species such as *Aspergillus fumigatus*, *Penicillium*, and *Rhizopus* have demonstrated significant potential for heavy metal removal (Kapoor & Viraraghavan, 1995). Fungal cell walls contain chitin, chitosan, and various polysaccharides that provide abundant binding sites for metal ions. Additionally, fungal biomass can be modified through chemical or physical treatments to enhance its adsorption capacity. For example, iron-coated fungal biomass has been shown to improve the removal efficiency of metals from complex solutions such as mine tailing leachates.

Microalgae have also emerged as highly effective biosorbents due to their unique biological and structural characteristics. Among them, *Chlorella vulgaris* is one of the most widely studied species for heavy metal removal (Zeraatkar et al., 2016). This microalga is characterized by a high surface area, rapid growth rate, and a cell wall rich in polysaccharides and proteins, which facilitate metal binding. Moreover, *C. vulgaris* can be cultivated under a variety of conditions, including autotrophic, heterotrophic, and mixotrophic modes, making it a flexible and sustainable source of biomass (Razzak et al., 2022b).

The mechanisms of heavy metal removal by microalgae involve both biosorption and bioaccumulation. Biosorption is a rapid process that occurs on the cell surface, while bioaccumulation involves the active transport of metal ions into the cell (Leong & Chang, 2020). Studies have demonstrated that *C. vulgaris* can effectively remove metals such as copper and cobalt from aqueous solutions, with high removal efficiencies observed in both single-component and multi-component systems (Cheng et al., 2017). The kinetics of biosorption are often described by pseudo-second-order models, indicating that chemisorption may be the rate-limiting step. Equilibrium data are commonly fitted using Langmuir and Freundlich isotherms, which provide insights into the adsorption capacity and surface heterogeneity of the biosorbent.

Several factors influence the efficiency of biosorption processes, including pH, temperature, contact time, initial metal concentration, and biomass dosage (Gupta & Rastogi, 2008). Among these, pH is one of the most critical parameters, as it affects both the speciation of metal ions and the ionization state of functional groups on the biosorbent surface. Optimization of these parameters is essential for maximizing the performance of biosorption systems.

In addition to biosorption, recent advancements in heavy metal remediation have explored the use of biochar, biosurfactants, and nanocomposite materials. Biochar, produced through the pyrolysis of biomass, has shown promising results due to its high surface area and functional group availability. Similarly, biosurfactants produced by microorganisms can enhance the solubility and mobility of heavy metals, facilitating their removal (Awual et al., 2019). Nanomaterials, although highly efficient, face challenges related to cost, scalability, and potential environmental risks.

Despite the promising potential of biosorption, several challenges remain to be addressed. These include the need for large-scale implementation, regeneration and reuse of biosorbents, and recovery of adsorbed metals. Additionally, the variability in biosorption performance under different environmental conditions necessitates further research to optimize process parameters and develop robust systems.



In conclusion, heavy metal contamination resulting from mining activities and industrial processes represents a significant environmental challenge. Biosorption offers a sustainable, cost-effective, and efficient solution for the removal of heavy metals from mine tailings and associated leachates. The use of biological materials such as fungal biomass and microalgae provides an environmentally friendly alternative to conventional treatment methods. Continued research and technological advancements in this field are essential for improving the efficiency, scalability, and practical applicability of biosorption processes, thereby contributing to sustainable environmental management and pollution control.

2. Materials and Methods

The algal biomass of *Chlorella vulgaris* was used as a biosorbent in this study. The biomass was obtained as a commercial product marketed as a dietary supplement

2.1 Analysis of Algal Biomass Properties

The point of zero charge (PZC) of *Chlorella vulgaris* was determined using the pH drift method. Approximately 0.5 g of algal biomass was added to 10 separate Erlenmeyer flasks, each containing 50 mL of 0.1 M NaNO₃ solution. The initial pH of the solutions was adjusted between 2 and 11 using 0.1 M HNO₃ and 0.1 M NaOH. The samples were agitated on a laboratory shaker for 24 hours. After equilibration, the final pH values were recorded, and the change in pH (ΔpH) was calculated using:

$$\Delta\text{pH} = \text{pH}_f - \text{pH}_i$$

The surface morphology and texture of the algal biomass were analyzed using a scanning electron microscope FTIR analysis was performed using a spectrometer to identify functional groups present on the biomass surface. Samples were prepared by mixing the biomass with potassium bromide (KBr) in a ratio of 0.25% (w/w), followed by pellet formation. Spectra were recorded in the range of 4000–400 cm⁻¹ using the transmission method.

2.2 Equilibrium Studies

Batch adsorption experiments were conducted using six 250 mL conical flasks. Each flask contained 0.5 g of *Chlorella vulgaris* biomass and 50 mL of metal ion solution. Copper (Cu²⁺) and cobalt (Co²⁺) solutions of varying concentrations (50, 100, 200, 600, 2000, and 5000 mg/L) were added. The pH was maintained under alkaline conditions by adding 1 M NaOH. The mixtures were agitated for 2 hours, after which they were filtered using a medium quantitative filter paper. The filtrate was collected for further analysis.

2.3 Determination of Metal Ion Concentration (F-AAS)

The concentrations of Cu(II) and Co(II) ions in the filtrate were determined using Flame Atomic Absorption Spectrometry (F-AAS) (Perkin Elmer Model 3100). A hollow cathode lamp specific to each metal was used, and measurements were performed using an acetylene–air flame. Calibration was carried out using standard solutions prior to analysis.



The adsorption capacity (q) and percentage removal (A) were calculated using:

$$q = \frac{(C_0 - C_e)V}{m}$$

$$A = \frac{(C_0 - C_e)}{C_0} \times 100$$

Where:

- C_0 = initial metal concentration (mg/L)
- C_e = equilibrium concentration (mg/L)
- V = volume of solution (L)
- m = mass of biosorbent (g)

2.4 Adsorption Isotherm Models

The adsorption isotherms were analyzed using:

- Freundlich model
- Langmuir model

Model fitting was evaluated using the coefficient of determination (R^2).

3. Results and Discussion

3.1 Characterization of Biosorbent

The physicochemical characteristics of the biosorbent play a crucial role in determining its adsorption efficiency and mechanism. In the present study, *Chlorella vulgaris* biomass was used as a biosorbent for the removal of heavy metals from mine tailings, and its surface properties were analyzed using PZC, SEM, and FTIR techniques.

The point of zero charge (PZC) is an important parameter that defines the pH at which the net surface charge of the biosorbent is zero. The experimental results showed that the PZC of *Chlorella vulgaris* lies within a moderately acidic range. At pH values lower than the PZC, the biosorbent surface becomes positively charged due to protonation of functional groups, whereas at pH values higher than the PZC, the surface acquires a negative charge due to deprotonation.

This behavior is particularly significant for the adsorption of metal cations such as Cu(II) and Co(II). At alkaline pH conditions, the negatively charged surface enhances electrostatic attraction between the biosorbent and positively charged metal ions, thereby improving adsorption efficiency. Scanning Electron Microscopy (SEM) analysis revealed that the surface of *Chlorella vulgaris* is irregular, rough, and highly porous. The presence of cavities, fissures, and heterogeneous surface structures provides a large surface area and multiple binding sites for metal ion adsorption. After biosorption, the SEM images typically show changes in surface morphology, indicating the occupation of pores and active sites by metal ions.

Fourier Transform Infrared (FTIR) spectroscopy further confirmed the presence of functional groups responsible for metal binding. The spectra indicated characteristic peaks corresponding to hydroxyl (-OH), carboxyl (-COOH), amino (-NH₂), and phosphate groups. These functional groups act as active sites for biosorption through



mechanisms such as complexation, coordination, and ion exchange. The combined results from PZC, SEM, and FTIR analyses suggest that *Chlorella vulgaris* possesses favorable surface characteristics for effective biosorption of heavy metals from contaminated environments such as mine tailings.

3.2 Effect of pH on Biosorption

The pH of the solution is one of the most influential factors affecting biosorption, as it governs both the speciation of metal ions and the surface charge of the biosorbent. In this study, the biosorption of Cu(II) and Co(II) ions was investigated over a pH range of 3 to 8. The results demonstrated that adsorption efficiency increased significantly with increasing pH. At lower pH values (pH 3–5), the removal efficiency was relatively low. This can be attributed to the high concentration of hydrogen ions (H^+) in the solution, which compete with metal ions for the available binding sites on the biosorbent surface. Additionally, at low pH, the functional groups such as carboxyl and amino groups become protonated, reducing their ability to bind with metal ions. As the pH increases, these groups undergo deprotonation, resulting in the development of negative charges on the biosorbent surface.

Maximum biosorption was observed around pH 8, where the adsorption capacity reached its peak. At this pH, electrostatic attraction between negatively charged biosorbent sites and positively charged metal ions is maximized. However, further increase in pH beyond this range may lead to precipitation of metal hydroxides, which can interfere with the adsorption process.

Therefore, pH 8 was selected as the optimum pH for subsequent experiments. These findings highlight the importance of pH optimization in designing efficient biosorption systems for wastewater treatment.

3.3 Effect of Contact Time and Adsorption Kinetics

Contact time is another critical parameter that influences the rate and extent of biosorption. The adsorption of Cu(II) and Co(II) ions onto *Chlorella vulgaris* was studied over different time intervals ranging from 15 to 180 minutes.

The results indicated that the adsorption process was rapid during the initial phase, with a significant amount of metal ions being removed within the first 30 minutes. This rapid uptake can be attributed to the availability of a large number of vacant active sites on the biosorbent surface.

As time progressed, the rate of adsorption gradually decreased and eventually reached equilibrium. The equilibrium time was found to be:

- **2 hours for Cu(II) ions**
- **0.5 hours for Co(II) ions**

The faster equilibrium observed for Co(II) may be due to its smaller ionic size or lower affinity toward the biosorbent compared to Cu(II).

To better understand the adsorption mechanism, kinetic models were applied. The pseudo-first-order model showed poor agreement with experimental data, as indicated by low correlation coefficients. In contrast, the pseudo-second-order model provided an excellent fit, suggesting that the adsorption process is controlled by chemisorption involving valence forces through sharing or exchange of electrons.

Furthermore, the intraparticle diffusion model was used to evaluate the role of diffusion in the adsorption process. The results indicated that intraparticle diffusion contributes to the adsorption mechanism but is not the sole rate-limiting step. This implies that multiple processes, including surface adsorption and pore diffusion, are involved.

3.4 Adsorption Isotherms

Adsorption isotherms describe the relationship between the amount of adsorbate adsorbed and its equilibrium concentration in solution. In this study, the equilibrium data were analyzed using Freundlich model, Langmuir model.

The Langmuir isotherm assumes monolayer adsorption onto a homogeneous surface with finite identical sites. The high correlation coefficient ($R^2 = 0.96$ for Cu(II)) indicates that the Langmuir model adequately describes the adsorption process.



The maximum adsorption capacities (q_{max}) obtained from the Langmuir model were:

- **30.1 mg/g for Cu(II)**
- **8.9 mg/g for Co(II)**

These values suggest that *Chlorella vulgaris* has a higher affinity for Cu(II) ions compared to Co(II). The Freundlich isotherm, which assumes heterogeneous surface adsorption, also showed good agreement with the experimental data ($R^2 = 0.94$ for Cu(II)). The Freundlich constant (n) was found to be greater than 1, indicating favorable adsorption conditions.

3.5 Adsorption in Binary System

In real-world applications such as mine tailings, multiple metal ions coexist and compete for adsorption sites. Therefore, binary system studies were conducted to evaluate the competitive adsorption behavior of Cu(II) and Co(II). The results showed a noticeable decrease in adsorption capacity in the presence of both metals. This reduction is attributed to competition for limited active sites on the biosorbent surface. The extended Langmuir and Jain–Snoeyink models were used to describe the adsorption behavior in binary systems. The adsorption capacities were reduced compared to single-component systems, confirming the competitive nature of adsorption. Interestingly, the difference in adsorption capacity between Cu(II) and Co(II) decreased in the binary system, indicating that Co(II) adsorption improves in the presence of Cu(II), possibly due to changes in surface properties or interaction effects.

3.6 Mechanism of Biosorption

The biosorption of heavy metals by *Chlorella vulgaris* involves a combination of physical and chemical processes.

The primary mechanisms include:

- **Electrostatic attraction** between negatively charged surface sites and metal ions
- **Ion exchange** between metal ions and functional groups
- **Complexation/chelation** with functional groups such as carboxyl and amino groups
- **Intraparticle diffusion** within the porous structure

FTIR analysis confirmed the involvement of functional groups in binding metal ions. The shift in peak positions after adsorption indicates interaction between metal ions and functional groups.

The higher adsorption capacity for Cu(II) suggests stronger binding affinity and better accessibility to active sites compared to Co(II).

3.7 Application to Mine Tailings

Mine tailings are complex matrices containing various heavy metals and contaminants. The results of this study demonstrate that *Chlorella vulgaris* is an effective biosorbent for removing heavy metals from such systems.

Its advantages include:

- Low cost and easy availability
- High adsorption capacity
- Environmentally friendly nature
- Ability to operate under mild conditions

However, the presence of multiple metal ions and other competing species may reduce adsorption efficiency. Therefore, optimization of process parameters is essential for practical applications.

4. Conclusion

In this study, *Chlorella vulgaris* was successfully utilized as a low-cost and readily available biosorbent for the removal of Cu(II) and Co(II) ions from aqueous solutions in both single-component and binary systems. Among the adsorption isotherm models applied, the Freundlich and Langmuir models showed the best fit to the experimental data. The coefficients of determination (R^2) were found to be 0.94 and 0.70 (Freundlich) and 0.96 and 0.60 (Langmuir) for Cu(II) and Co(II), respectively. These results indicate that the adsorption process predominantly follows monolayer adsorption and that *Chlorella vulgaris* exhibits microporous characteristics.



The Freundlich constant (n) suggested favorable adsorption and a relatively homogeneous surface. The maximum adsorption capacity (q_{max}) was higher for Cu(II) ions (30.1 mg/g) compared to Co(II) ions (8.9 mg/g), indicating a stronger affinity of the biosorbent toward copper ions. Overall, the results demonstrate that Cu(II) ions have a higher affinity and better accessibility to the active sites of *Chlorella vulgaris* compared to Co(II) ions. Based on these findings, *Chlorella vulgaris* can be considered an effective and promising biosorbent for the removal of heavy metals, particularly copper and cobalt ions, from contaminated water.

References

- Anser, M. K., Yousaf, Z., Nassani, A. A., Abro, M. M. Q., Zaman, K., & Kabbani, A. (2020). Dynamic linkages between ecological footprint, human capital, and economic growth: Evidence from emerging economies. *Environmental Science and Pollution Research*, 27(28), 34993–35007. <https://doi.org/10.1007/s11356-020-09598-3>
- Awual, M. R., Hasan, M. M., & Asiri, A. M. (2019). Novel chelating ligand for selective detection and removal of toxic metals. *Chemical Engineering Journal*, 356, 438–448.
- Cheng, J., Yin, W., Chang, Z., Lundholm, N., & Jiang, Z. (2017). Biosorption capacity and kinetics of heavy metals by *Chlorella vulgaris*. *Bioresource Technology*, 244, 814–821.
- Gupta, V. K., & Rastogi, A. (2008). Biosorption of lead from aqueous solutions by green algae *Spirogyra* species: Kinetics and equilibrium studies. *Journal of Hazardous Materials*, 152(1), 407–414. <https://doi.org/10.1016/j.jhazmat.2007.07.028>
- Hassan, S. H. A., Talat, M., & Raihan, O. (2017). Bioremediation of heavy metals using microbial systems. *International Journal of Environmental Science and Technology*, 14(6), 1229–1246.
- Hong, Y. S., Song, K. H., & Chung, J. Y. (2011). Health effects of chronic arsenic exposure. *Journal of Preventive Medicine and Public Health*, 44(3), 85–92.
- 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>
- Johnson, D. B. (2014). Biomining—Biotechnologies for extracting and recovering metals from ores and waste materials. *Current Opinion in Biotechnology*, 30, 24–31.
- Karn, S. K., Chakrabarty, S., & Reddy, M. S. (2021). Heavy metal contamination in water and their hazardous effects. *Environmental Science and Pollution Research*, 28, 1–15.
- Kapoor, A., & Viraraghavan, T. (1995). Fungal biosorption—An alternative treatment option for heavy metal bearing wastewaters: A review. *Bioresource Technology*, 53(3), 195–206.
- Kumar, V., Singh, J., Kumar, P., & Singh, S. (2015). Heavy metal contamination in environment and their toxicological effects. *Journal of Environmental Biology*, 36(2), 291–302.
- Leong, Y. K., & Chang, J. S. (2020). Bioremediation of heavy metals using microalgae: Recent advances and mechanisms. *Bioresource Technology*, 303, 122886.
- Liu, J., Goyer, R. A., & Waalkes, M. P. (2023). Toxic effects of metals. In C. D. Klaassen (Ed.), *Casarett and Doull's Toxicology: The Basic Science of Poisons* (9th ed.). McGraw-Hill.



Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., & Idris, A. M. (2022). Impact of heavy metals on the environment and human health. *Environmental Science and Pollution Research*, 29, 1–16.

Priya, A., Senthil Kumar, P., & Vo, D. V. N. (2022). Microalgae in wastewater treatment: Current trends and future prospects. *Chemosphere*, 286, 131764.

Rawlings, D. E., Dew, D., & du Plessis, C. (2003). Biomineralization of metal-containing ores and concentrates. *Trends in Biotechnology*, 21(1), 38–44.

Razzak, S. A., Hossain, M. M., Lucky, R. A., Bassi, A. S., & de Lasa, H. (2022a). Integrated CO₂ capture, wastewater treatment and biofuel production by microalgae culturing. *Renewable and Sustainable Energy Reviews*, 27, 622–653.

Razzak, S. A., et al. (2022b). Microalgae-based bioremediation for sustainable wastewater treatment. *Bioresource Technology Reports*, 17, 100892.

Shanab, S. M. M., Essa, A., & Shalaby, E. (2012). Bioremediation of heavy metals by algae. *African Journal of Biotechnology*, 11(4), 825–833.

Shrestha, S., Son, G., Lee, S. H., & Lee, T. G. (2021). Isotherm and thermodynamic studies of adsorption process. *Journal of Environmental Chemical Engineering*, 9(2), 104–112.

Suresh Kumar, K., Dahms, H. U., Won, E. J., Lee, J. S., & Shin, K. H. (2015). Microalgae—A promising tool for heavy metal remediation. *Ecotoxicology and Environmental Safety*, 113, 329–352.

Taylor, M. P., Mackay, A. K., Hudson-Edwards, K. A., & Holz, E. (2018). Soil Cd, Cu, Pb and Zn contaminants around mining and smelting sites. *Environmental Pollution*, 236, 452–464.

Volesky, B. (2007). Biosorption and me. *Water Research*, 41(18), 4017–4029.

Wang, J., & Chen, C. (2009). Biosorbents for heavy metals removal and their future. *Biotechnology Advances*, 27(2), 195–226.

Yang, L., Chen, J., Wang, J., & Liu, Y. (2020). Health risk assessment of heavy metals. *Environmental Research*, 187, 109–120.

Yadav, I. C., Devi, N. L., Singh, V. K., Li, J., Zhang, G., & Covaci, A. (2018). Heavy metals in environment and human health. *Environmental Science and Pollution Research*, 25, 1–14.

Zeraatkar, A. K., Ahmadzadeh, H., Talebi, A. F., Moheimani, N. R., & McHenry, M. P. (2016). Potential use of algae for heavy metal bioremediation. *Journal of Environmental Management*, 181, 817–831.