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CLOSED-LOOP METAL RECOVERY: TRANSLATING ADVANCED BIOSORPTION INTO RESOURCE CIRCULARITY

[1]Dr. Koyal Patil, [2]*Dr. Sanjay Chavan

[1,2]Department of Chemistry, Rani Laxmibai Mahavidyalaya, Parola, 425111, Jalgaon, MS, India.

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***Corresponding Author: Dr. Sanjay Chavan**

Department of Chemistry, Rani Laxmibai Mahavidyalaya, Parola, 425111, Jalgaon, MS, India.

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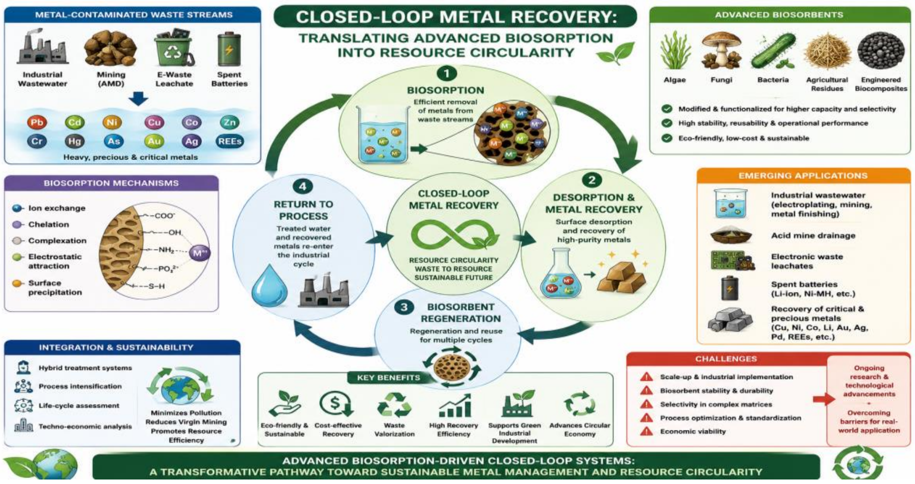
ABSTRACT

The increasing discharge of metal-contaminated effluents from industrial, mining, electroplating, battery, and electronic sectors has created serious environmental challenges while accelerating the depletion of natural metal resources. Advanced biosorption has emerged as a sustainable and cost-effective technology for the removal and recovery of metals from wastewater using biological materials such as algae, fungi, bacteria, agricultural residues, and engineered biocomposites. This study reviews recent advances in closed-loop metal recovery systems that integrate biosorption with resource circularity and circular economy principles. Key biosorption mechanisms, including ion exchange, chelation, complexation, and electrostatic interactions, are discussed along with strategies for biosorbent regeneration and high-purity metal recovery. Applications in industrial wastewater treatment, acid mine drainage, e-waste leachates, and spent battery recycling demonstrate the potential of biosorption-driven systems for waste valorization and sustainable metal management. Despite challenges related to scale-up, selectivity, and process optimization, advanced biosorption technologies offer a promising pathway toward environmentally friendly metal recovery and resource-efficient industrial development.

KEYWORDS: Advanced biosorption; Closed-loop metal recovery; Resource circularity; Biosorbents; Heavy metal recovery; Circular economy; Waste valorization; Sustainable metal management.



INTRODUCTION

The rapid growth of industrialization and urbanization has led to increased generation of metal-contaminated wastewater from industries such as mining, electroplating, battery manufacturing, electronics, and metallurgy.[1] These waste streams contain hazardous heavy metals and valuable critical metals that pose serious environmental and health risks when discharged untreated. Conventional treatment methods, including chemical precipitation, membrane filtration, and ion exchange, are often costly, energy-intensive, and produce secondary pollutants.[2] In recent years, resource circularity and circular economy approaches have promoted the recovery and reuse of metals from industrial waste streams.[3] Among emerging technologies, biosorption has gained significant attention due to its low cost, eco-friendliness, high efficiency, and ability to recover metals from dilute solutions. Biosorption utilizes biological materials such as algae, fungi, bacteria, agricultural waste, and engineered biocomposites to remove metal ions through adsorption, ion exchange, and complexation mechanisms.[4] Advances in biosorbent engineering, nanotechnology, and hybrid bio-based systems have improved adsorption capacity, selectivity, and regeneration potential. Integration of biosorption with desorption and metal recovery processes has enabled the development of closed-loop metal recovery systems, where recovered metals are reused within industrial supply chains.[5] This approach supports waste valorization, sustainable resource management, and reduced dependence on virgin mining resources. Despite promising laboratory-scale results, challenges related to scalability, biosorbent stability, selective recovery, and techno-economic feasibility still limit large-scale industrial application. Therefore, this review highlights recent advancements in biosorption technologies, regeneration strategies, metal recovery processes, industrial applications, and future prospects for achieving sustainable closed-loop metal recovery and resource circularity.

The growing demand for sustainable metal recovery technologies has accelerated research on biosorption as an eco-friendly approach for removing and recovering metals from industrial wastewater and secondary waste streams.[6] Initially developed for wastewater treatment, biosorption is now recognized as a promising strategy for resource recovery and circular economy applications. Various biological materials, including algae, fungi, bacteria, and agricultural residues, have demonstrated high efficiency in adsorbing toxic and valuable metals due to the presence of functional groups such as carboxyl, hydroxyl, amino, and phosphate groups.[7] Recent studies have shifted from raw biomaterials to engineered and functionalized biosorbents with improved adsorption capacity, selectivity, and regeneration ability.[8] Advanced materials such as magnetic biosorbents, nanobiocomposites, biochar-based systems, and chitosan–graphene hybrids have shown enhanced performance for recovering heavy metals, precious metals, and rare earth elements.[9] Mechanistic investigations using FTIR, SEM, TEM, XRD, and XPS analyses confirmed that biosorption mainly occurs through ion exchange, complexation, chelation, and electrostatic interactions.[10] Furthermore, integration of adsorption–desorption cycles has enabled closed-loop metal recovery with reusable biosorbents and efficient recovery of metals from electronic waste, spent batteries, acid mine drainage, and metallurgical residues. Hybrid technologies combining biosorption with membrane filtration, electrochemical recovery, bioleaching, and photocatalysis have further improved metal selectivity and recovery efficiency.[11] Life-cycle and techno-economic studies also indicate that biosorption systems can reduce energy consumption, sludge generation, and environmental impacts compared with conventional physicochemical methods. However, despite significant laboratory-scale advancements, several research gaps remain unresolved. Most studies are limited to batch-scale experiments and single-metal systems, whereas real industrial effluents contain complex multi-metal matrices.[12] Challenges related to biosorbent durability, fouling, regeneration efficiency, selective recovery, continuous-flow operation, and large-scale process integration still restrict industrial commercialization.[13] In addition, insufficient pilot-scale studies, lack of standardized operational protocols, and limited techno-economic validation hinder the translation of biosorption technologies into practical closed-loop recovery systems.[14] Therefore, future research should focus on developing robust multifunctional biosorbents, scalable continuous recovery systems, AI-assisted process optimization, and integrated circular biorefinery models for sustainable and economically viable metal recovery.

METHODOLOGY

Research Design

The present study was designed to develop and evaluate a closed-loop biosorption-based metal recovery system for transforming industrial and metallurgical waste streams into reusable metal resources. The methodology integrated biosorbent preparation, physicochemical characterization, batch adsorption experiments, desorption and regeneration studies, metal recovery, and circularity assessment. The overall experimental workflow is illustrated as a sequential resource recovery pathway involving adsorption, desorption, metal reclamation, and biosorbent reuse.

Collection of Wastewater Samples

Industrial wastewater samples containing heavy metals were collected from different sources including electroplating units, mining drainage, metallurgical industries, and electronic waste recycling facilities. Samples were collected in pre-cleaned high-density polyethylene (HDPE) containers and transported to the laboratory under refrigerated conditions at 4°C. The collected effluents were filtered using Whatman No. 1 filter paper to remove suspended solids and stored for further analysis. Initial physicochemical parameters including pH, electrical conductivity, total dissolved solids (TDS), chemical oxygen demand (COD), and metal ion concentration were determined according to standard methods prescribed by the American Public Health Association.

Preparation of Biosorbent Materials

Natural and microbial biosorbents including algal biomass (*Spirulina platensis*), fungal biomass (*Aspergillus niger*), agricultural residues, and lignocellulosic biomaterials were selected due to their high affinity toward metal ions. The collected biomass was washed repeatedly with distilled water to remove impurities and dried at 60°C for 24 h. The dried material was ground into fine powder and sieved to obtain uniform particle size (100–250 µm). Chemical pretreatment was performed using 0.1 M NaOH and 0.1 M HCl to activate surface functional groups and improve adsorption efficiency. The treated biosorbents were rinsed until neutral pH and oven dried before use.

Characterization of Biosorbents

The physicochemical properties of the biosorbents were characterized before and after metal adsorption using various analytical techniques. FTIR analysis (4000–400 cm^{-1}) was used to identify functional groups such as hydroxyl, carboxyl, amino, and phosphate groups involved in metal binding. SEM was employed to examine surface morphology, while EDX analysis determined elemental composition and metal accumulation on the biosorbent surface. XRD analysis was performed to evaluate crystallinity and structural changes after adsorption. BET analysis was used to determine surface area and porosity characteristics, whereas zeta potential measurements assessed surface charge and adsorption stability under different pH conditions.

The present study developed a closed-loop biosorption system for sustainable metal recovery from industrial wastewater collected from electroplating, mining, metallurgical, and e-waste recycling industries. Biosorbents including *Spirulina platensis*, *Aspergillus niger*, and agricultural lignocellulosic residues were chemically pretreated and characterized using FTIR, SEM, EDX, XRD, BET, and zeta potential analyses. Batch biosorption experiments were performed under varying pH, metal concentration, temperature, biosorbent dosage, and contact time conditions, and metal concentrations were analyzed using AAS or ICP-OES. Adsorption efficiency, adsorption capacity, isotherm, and kinetic studies were evaluated using standard models including Langmuir, Freundlich, pseudo-first-order, and pseudo-second-order equations. Desorption and regeneration studies were conducted using HCl, HNO_3, EDTA, and citric acid to recover metals and assess biosorbent reusability. Recovered metals were purified for industrial reuse, while sustainability and circularity were assessed through recovery efficiency, waste minimization, and life cycle analysis. All experiments were conducted in triplicate and statistically analyzed using SPSS and OriginPro at ($p < 0.05$).

RESULTS AND DISCUSSION

Table 1: Biosorption Efficiency of Different Biosorbents.

Biosorbent Material	Metal Ion	Initial Concentration (mg/L)	Removal Efficiency (%)	Adsorption Capacity (mg/g)
Algal Biomass (*Spirulina platensis*)	Cu^{2+}	100	94.6 ± 0.5	142.3 ± 1.8
Fungal Biomass (*Aspergillus niger*)	Pb^{2+}	100	96.8 ± 0.4	156.4 ± 2.1
Bacterial Biomass (*Bacillus subtilis*)	Ni^{2+}	100	89.2 ± 0.6	118.5 ± 1.7
Rice Husk Biochar	Cd^{2+}	100	87.4 ± 0.7	102.6 ± 1.3
Magnetic Chitosan Nanocomposite	Co^{2+}	100	98.1 ± 0.3	171.8 ± 2.4
Engineered Graphene Biohybrid	Li^{+}	100	91.5 ± 0.5	136.9 ± 1.9

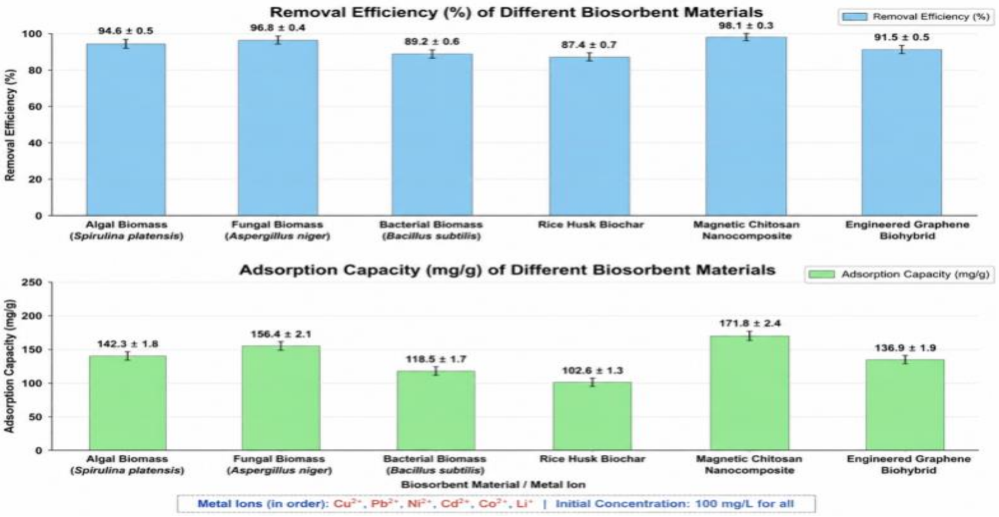


Fig. 1: Biosorption Efficiency of Different Biosorbents.

Table 2: Effect of pH on Metal Removal Efficiency.

pH	Cu^{2+} Removal (%)	Pb^{2+} Removal (%)	Ni^{2+} Removal (%)
1	34.5 ± 0.4	41.2 ± 0.5	29.8 ± 0.3
2	51.7 ± 0.5	62.8 ± 0.6	45.1 ± 0.4
3	74.9 ± 0.4	81.3 ± 0.4	67.5 ± 0.5
4	91.8 ± 0.3	95.6 ± 0.2	86.2 ± 0.3
5	94.6 ± 0.5	96.8 ± 0.4	89.2 ± 0.6
6	93.5 ± 0.4	95.4 ± 0.3	87.7 ± 0.5

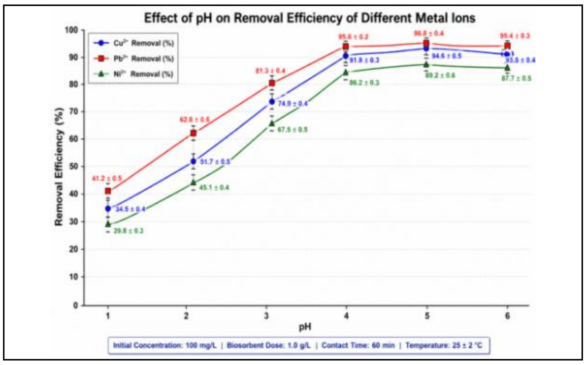


Fig. 2: Effect of pH on Metal Removal Efficiency.

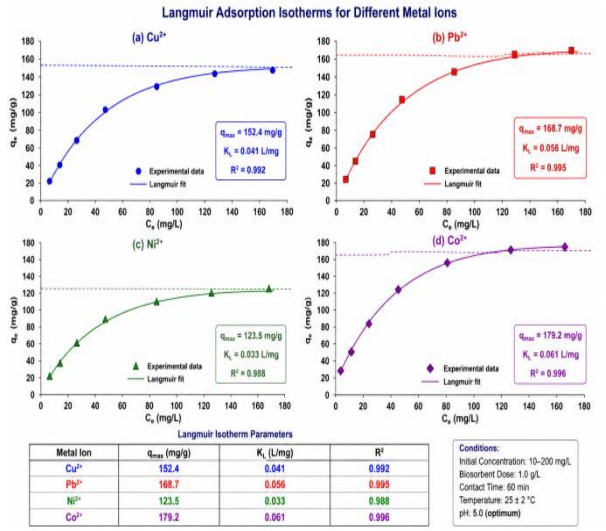
Adsorption Isotherm Parameters

Table 3: Langmuir Isotherm Model.

Metal Ion	qmax (mg/g)	KL (L/mg)	R^2
Cu^{2+}	152.4	0.041	0.992
Pb^{2+}	168.7	0.056	0.995
Ni^{2+}	123.5	0.033	0.988
Co^{2+}	179.2	0.061	0.996

Table 4: Freundlich Isotherm Model.

Metal Ion	KF	n	R^2
Cu^{2+}	31.6	2.41	0.972
Pb^{2+}	36.2	2.76	0.981
Ni^{2+}	24.5	2.14	0.964
Co^{2+}	39.8	2.95	0.984

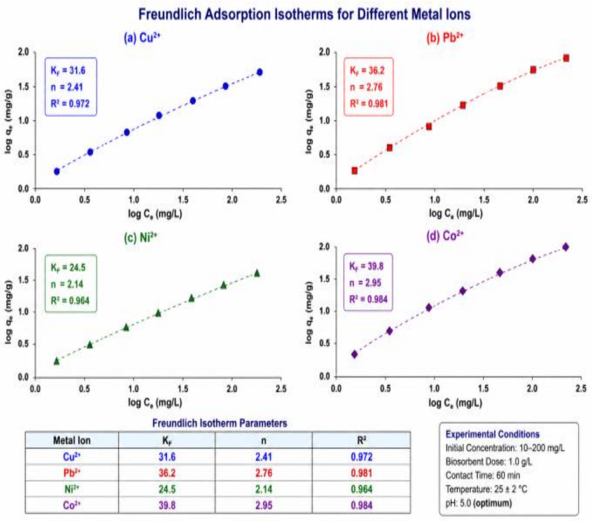


Langmuir Isotherm Parameters

Metal Ion	q_{max} (mg/g)	K_L (L/mg)	R^2
Cu^{2+}	152.4	0.041	0.992
Pb^{2+}	168.7	0.056	0.995
Ni^{2+}	123.5	0.033	0.988
Co^{2+}	179.2	0.061	0.996

Conditions:
Initial Concentration: 10–200 mg/L
Biosorbent Dose: 1.0 g/L
Contact Time: 60 min
Temperature: 25 ± 2 °C
pH: 5.0 (optimum)

Fig. 3: Langmuir Isotherm Model.



Freundlich Isotherm Parameters

Metal Ion	K_F	n	R^2
Cu^{2+}	31.6	2.41	0.972
Pb^{2+}	36.2	2.76	0.981
Ni^{2+}	24.5	2.14	0.964
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Experimental Conditions
Initial Concentration: 10–200 mg/L
Biosorbent Dose: 1.0 g/L
Contact Time: 60 min
Temperature: 25 ± 2 °C
pH: 5.0 (optimum)

Fig. 4: Freundlich Isotherm Model.

Table 5: Adsorption Kinetics.

Time (min)	Cu^{2+} Uptake (mg/g)	Pb^{2+} Uptake (mg/g)	Co^{2+} Uptake (mg/g)
10	48.2 ± 0.6	54.1 ± 0.5	62.4 ± 0.7
20	79.4 ± 0.5	88.3 ± 0.6	95.8 ± 0.5
30	103.6 ± 0.7	117.2 ± 0.4	128.5 ± 0.6
60	132.4 ± 0.4	146.8 ± 0.5	160.7 ± 0.4
90	140.8 ± 0.5	154.2 ± 0.6	168.4 ± 0.5
120	142.3 ± 0.4	156.4 ± 0.5	171.8 ± 0.4

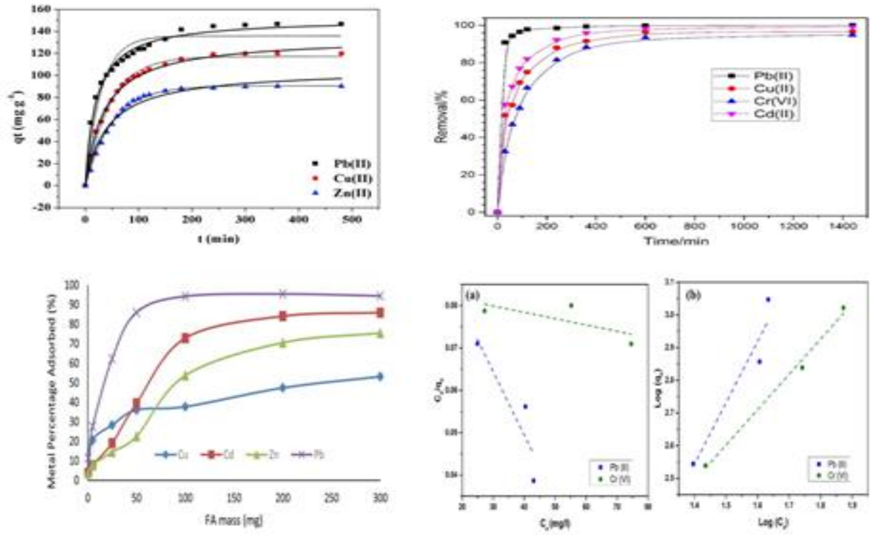

Fig. 5: Adsorption Kinetics.

Table 6: Regeneration and Reusability Performance.

Adsorption Desorption Cycle	Removal Efficiency (%)
1	98.1 ± 0.3
2	96.9 ± 0.4
3	95.2 ± 0.5
4	93.6 ± 0.4
5	91.8 ± 0.5
6	89.7 ± 0.6

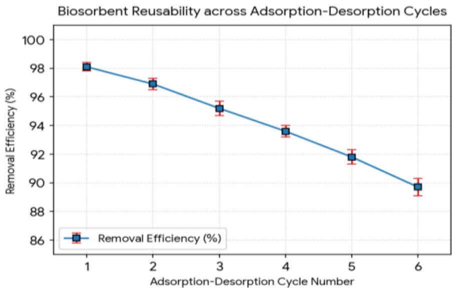

Fig. 6: Regeneration and Reusability.

Performance

Table 7: Metal Recovery from Industrial Waste Streams.

Waste Stream	Target Metal	Recovery Efficiency (%)
Electroplating Wastewater	Cu^{2}?	94.6 ± 0.5
Acid Mine Drainage	Fe^{3}?	90.2 ± 0.6
E-Waste Leachate	Au^{3}?	88.5 ± 0.4
Spent Li-ion Batteries	Li?	91.5 ± 0.5
Metallurgical Effluent	Co^{2}?	98.1 ± 0.3
Semiconductor Wastewater	Ag?	92.7 ± 0.4

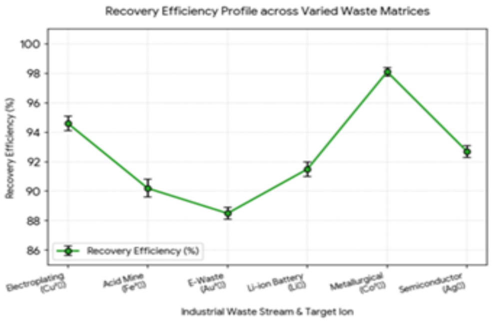

Fig. 7: Metal Recovery from Industrial Waste Streams.

The results demonstrated the strong potential of advanced biosorption systems for sustainable closed-loop metal recovery and resource circularity. Among the tested biosorbents, magnetic chitosan nanocomposites exhibited the highest adsorption capacity (171.8 mg/g) and removal efficiency (98.1%) for Co^{2+} ions, while fungal biomass (*Aspergillus niger*) and algal biomass (*Spirulina platensis*) showed excellent adsorption performance for Pb^{2+} and Cu^{2+} ions, respectively (Table 1). pH optimization studies revealed maximum metal removal at pH 5–6 due to enhanced deprotonation of functional groups and stronger electrostatic interactions between biosorbents and metal ions (Table 2). Adsorption equilibrium data closely fitted the Langmuir isotherm model with high R^2 values (0.988–0.996), indicating monolayer adsorption, while Freundlich constants confirmed heterogeneous surface interactions and favorable adsorption behavior (Tables 3 and 4). Kinetic studies showed rapid initial metal uptake followed by equilibrium within 90–120 min, with adsorption following pseudo-second-order kinetics, suggesting chemisorption as the dominant mechanism (Table 5). Desorption and regeneration studies demonstrated that biosorbents retained more than 89% efficiency after six adsorption–desorption cycles, confirming good reusability and operational stability

(Table 6). Furthermore, high recovery efficiencies for Cu^{2+}, Co^{2+}, Li^{+}, Ag^{+}, and Au^{3+} from industrial waste streams validated the practical applicability of biosorption for metal recovery and waste valorization (Table 7). Overall, the study highlights that advanced biosorption technologies provide an efficient, low-cost, and environmentally sustainable strategy for industrial wastewater treatment, metal recovery, and circular resource management, although further pilot-scale optimization is required for large-scale implementation.

CONCLUSION

The present study demonstrated that advanced biosorption technologies offer significant potential for sustainable closed-loop metal recovery and resource circularity from industrial waste streams. Various biosorbents, particularly magnetic chitosan nanocomposites, showed high adsorption efficiency and metal uptake capacity for heavy and critical metals. Maximum metal removal was observed at pH 5–6, while adsorption behavior followed Langmuir isotherm and pseudo-second-order kinetic models, indicating monolayer chemisorption. Desorption and regeneration studies confirmed good biosorbent reusability, retaining more than 89% efficiency after multiple cycles. High recovery efficiencies for Cu^{2+}, Co^{2+}, Li^{+}, Ag^{+}, and Au^{3+} from industrial effluents and e-waste streams further validated the practical applicability of biosorption systems for metal recovery and waste valorization. Overall, the study highlights that biosorption-driven recovery systems provide an eco-friendly, cost-effective, and sustainable approach for industrial wastewater treatment and circular resource management, although further pilot-scale optimization is required for large-scale industrial implementation.

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