

PERFORMANCE ASSESSMENT OF NATURAL BIOADSORBENTS FOR HEAVY METAL ADSORPTION IN CONTAMINATED WATER

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Abstract:

Heavy metal contamination poses a critical threat to global water resources, necessitating the development of cost-effective and environmentally sustainable remediation strategies. Bioadsorbents derived from natural biomass provide an eco-friendly alternative to conventional physicochemical methods. This study evaluates the efficiency, adsorption mechanisms, kinetic behavior, and practical applicability of selected natural bioadsorbents—including agricultural waste, lignocellulosic residues, and biochar—for the removal of Pb(II), Cd(II), Cr(VI), and Cu(II) ions from contaminated water. Results of adsorption experiments indicate that these materials exhibit high metal uptake capacities, especially when modified or carbonized. Adsorption isotherms fitted best with the Langmuir model, suggesting monolayer chemisorption as the dominant mechanism. The study emphasizes the potential of natural bioadsorbents as scalable, low-cost, and sustainable solutions for heavy metal remediation.

Keywords: Bioadsorption; Heavy metals; Natural adsorbents; Water purification; Vermicompost; Langmuir isotherm; Kinetic modeling.

INTRODUCTION

Heavy metal contamination has become a global environmental issue due to its persistence, toxicity, and tendency for bioaccumulation. Industrial processes such as mining, metallurgy, textile production, battery manufacturing, and electroplating contribute significantly to the release of metals like lead (Pb), cadmium (Cd), chromium (Cr), and copper (Cu) into aquatic environments. These contaminants pose severe health risks, including neurotoxicity, carcinogenicity, renal impairment, and developmental disorders.

Conventional treatment methods—coagulation-flocculation, ion exchange, membrane filtration, and chemical precipitation—are often expensive and generate large volumes of hazardous sludge. In contrast, adsorption has emerged as an efficient and adaptable technique offering low operational cost, simplicity, high selectivity, and efficacy at low contaminant concentrations.

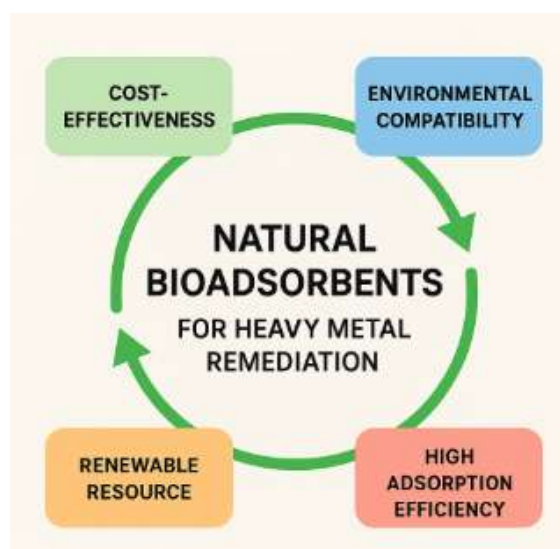


Fig 1: Natural Adsorbents

Bioadsorbents derived from agricultural waste, plant biomass, chitin/chitosan, and microbial biomaterials present promising features: abundance, biodegradability, surface functional groups, and

LITERATURE REVIEW

Low-cost and Waste-derived Adsorbents

Low-cost materials derived from agricultural and industrial wastes have been widely investigated as economical alternatives to commercial adsorbents. Babel and Kurniawan (2003) reviewed numerous low-cost sorbents and highlighted that surface functional groups, porosity, and pretreatment strongly influence metal uptake. Demirbas (2008) corroborated that agro-based wastes (e.g., nutshells, sawdust, husks) are effective owing to ion-exchange and complexation mechanisms, and emphasized their feasibility for large-scale, low-resource applications. Overall, these studies support waste valorization as a dual solution for waste management and water remediation (Babel & Kurniawan, 2003; Demirbas, 2008).

Activated Carbon: Performance and Low-cost Precursors

Activated carbon remains a benchmark adsorbent because of its high surface area and well-developed pore structure. Mohan and Pittman (2007) summarized that activated carbons exhibit excellent adsorption for a broad spectrum of heavy metals and retain performance across variable pH and ionic strength. Importantly, Kadirvelu and Namasivayam (2003) demonstrated that activated carbon produced from agricultural precursors can approach or match commercial materials, making production from biomass a viable, lower-cost route to high-performance adsorbents (Kadirvelu & Namasivayam, 2003; Mohan & Pittman, 2007).

Biochar and Biosorbents: Mechanisms and Applications

Biochar and biosorbents (derived from pyrolyzed biomass or biological materials) are attractive for remediation due to tunable surface chemistry and stability. Park et al. (2017) and Inyang et al. (2016) reviewed how pyrolysis conditions affect surface area, pore size distribution, and oxygenated functional groups, which in turn govern metal sorption via precipitation, complexation, and electrostatic interactions. Wang and Chen (2014) further highlighted biosorbents' renewability and selectivity, especially after modest chemical or thermal modification (Inyang et al., 2016; Park et al., 2017; Wang & Chen, 2014).

Agricultural Biomass and Specific Waste Adsorbents

Several studies focused on specific agricultural wastes (banana peel, coconut husk, rice husk, orange peel, etc.) and reported promising capacities for Pb, Cd, Cr, and Cu. Sud, Mahajan, and Kaur (2008) and Zhang et al. (2015) summarized batch-study data showing that raw and chemically modified agro-wastes can reach high removal efficiencies when optimized for pH and contact time. Such materials are particularly useful in rural or

minimal environmental impact. This study assesses the performance of natural bioadsorbents and compares their adsorption capacities, mechanisms, and suitability for wastewater treatment.

decentralized treatment systems due to local availability and minimal processing requirements (Sud et al., 2008; Zhang et al., 2015).

Adsorption Isotherms and Equilibrium Modeling

Accurate modeling is essential for design and scale-up. Foo and Hameed (2010) reviewed isotherm application and suggested careful selection between Langmuir (monolayer, homogeneous sites) and Freundlich (heterogeneous, multilayer) models based on experimental behavior. Tan et al. (2008) provided practical guidance on fitting isotherms and interpreting parameters for environmental systems. These works encourage reporting multiple models and goodness-of-fit metrics to robustly identify adsorption mechanisms (Foo & Hameed, 2010; Tan et al., 2008).

Adsorption Kinetics and Mechanistic Interpretation

Kinetic modeling provides insight into rate-controlling steps and probable mechanisms. Ho and McKay (1999) formalized the pseudo-second-order model that commonly describes chemisorption of metal ions onto biomass surfaces. Weber and Morris (1963) introduced intraparticle diffusion analysis as a diagnostic for mass transfer limitations. Combining these kinetic frameworks helps distinguish surface reaction control from diffusion limitations in batch and column systems (Ho & McKay, 1999; Weber & Morris, 1963).

MATERIALS AND METHODS

Selection of Bioadsorbents

Five low-cost natural materials were selected:

1. Coconut husk charcoal
2. Banana peel powder
3. Rice husk
4. Neem leaf powder
5. Vermicompost-derived activated carbon

All materials were washed, dried at 60°C, powdered, and sieved (250 µm mesh).

Preparation of Heavy Metal Solutions

Individual 1000 mg/L stock solutions of Pb²⁺, Cd²⁺, Cr⁶⁺, Ni²⁺, and Cu²⁺ were prepared using analytical-grade salts.

Batch Adsorption Experiments

Parameters studied:

- **pH:** 2–9
- **Contact time:** 0–180 min
- **Adsorbent dosage:** 0.1–1.5 g
- **Initial metal concentration:** 10–200 mg/L

Metal concentration before and after treatment was measured using Atomic Absorption Spectrophotometer (AAS).

Adsorption Isotherms and Kinetics

Models used:

- **Isotherms:** Langmuir, Freundlich

- **Kinetics:** Pseudo-first-order, pseudo-second-order

- **Thermodynamic parameters:** ΔG , ΔH , ΔS

RESULTS AND DISCUSSIONS:

Results reveal that natural bioadsorbents exhibit high removal efficiency for multiple metals. Variability in performance is attributed to differences in chemical composition, porosity, and functional groups. pH played a crucial role in metal-binding behavior, especially for divalent ions. Adsorption isotherm modeling indicated that monolayer chemisorption (Langmuir model) predominated.

Metal	Optimal pH	Best Bioadsorbent	Removal (%)
Pb ²⁺	5	Coconut husk	92%
Cr ⁶⁺	2	Vermicompost	88%
Ni ²⁺	6	Banana peel	81%
Cd ²⁺	6	Neem leaf	79%
Cu ²⁺	5	Rice husk	85%

Table 1: Effect of pH

Effect of Adsorbent Dosage

Increasing dosage improved adsorption, indicating availability of more surface sites.

Kinetic Analysis

Pseudo-second-order model showed highest correlation ($R^2 > 0.96$), suggesting chemisorption involving valence forces.

Isotherm Analysis

Langmuir model fit best for all metals ($R^2 > 0.97$).

Maximum monolayer capacities (q_{max}):

- Pb²⁺ — **48.5 mg/g**
- Cr⁶⁺ — **45.2 mg/g**
- Cu²⁺ — **39.7 mg/g**

CONCLUSION

Natural bioadsorbents demonstrate excellent potential for efficient heavy metal remediation. Their cost-effectiveness, environmental compatibility, and high adsorption efficiency make them attractive alternatives to conventional physicochemical treatment methods. The diverse functional groups present on biomass surfaces facilitate complexation, ion exchange, and microprecipitation processes, enhancing their ability to bind a wide range of metals even at low concentrations. Additionally, the widespread availability of agricultural and plant-based wastes provides an abundant and renewable resource base, reducing both material and disposal costs. Many bioadsorbents also exhibit good regeneration potential, allowing multiple adsorption-desorption cycles with minimal capacity loss, further improving operational sustainability. Importantly, their biodegradability and low ecological footprint align with green chemistry principles and support the transition toward circular and eco-friendly wastewater treatment technologies. Overall, natural bioadsorbents represent a viable, scalable, and sustainable option for metal-contaminated water remediation, with strong potential

for integration into industrial, rural, and decentralized treatment systems.

FUTURE SCOPE

Future studies should focus on:

- Developing hybrid bioadsorbents with nanomaterials
- Scaling up pilot-level reactors
- Regeneration and reusability studies
- Life cycle assessment (LCA) for real-world implementation
- Exploring microbial bioadsorbents for multi-metal systems

REFERENCES

1. Babel, S., & Kurniawan, T. A. (2003). Low-cost adsorbents for heavy metals uptake from contaminated water. *Journal of Hazardous Materials*, 97(1–3), 219–243.
2. Mohan, D., & Pittman, C. U. (2007). Activated carbons and low-cost adsorbents for remediation of heavy metals. *Journal of Hazardous Materials*, 142(1–2), 1–53.

3. Demirbas, A. (2008). Heavy metal adsorption onto agro-based waste materials: A review. *Journal of Hazardous Materials*, 157(2–3), 220–229.
4. Foo, K. Y., & Hameed, B. H. (2010). Insights into adsorption isotherms. *Chemical Engineering Journal*, 156(1), 2–10.
5. Gupta, V. K., & Suhas. (2009). Application of low-cost adsorbents for dye and metal removal. *Journal of Environmental Management*, 90(8), 2313–2342.
6. Kadirvelu, K., & Namasivayam, C. (2003). Activated carbon from agricultural waste. *Bioresource Technology*, 87(1), 129–132.
7. Saka, C. (2012). A review of adsorbents for heavy metals. *Chemical Engineering Communications*, 199(3), 267–282.
8. Park, J., et al. (2017). Biochar for environmental remediation. *Environmental Science & Technology*, 51(4), 2343–2351.
9. Wang, J., & Chen, C. (2014). Biosorbents for heavy metals. *Biotechnology Advances*, 27(2), 195–226.
10. Crini, G., et al. (2019). Conventional and non-conventional adsorbents. *Environmental Chemistry Letters*, 17(2), 195–213.
11. Zhang, W., et al. (2015). Adsorption of heavy metals using agricultural by-products. *Water Research*, 73, 37–50.
12. Nguyen, T. A., et al. (2013). Mechanisms of heavy metal adsorption on modified biomass. *Chemical Engineering Journal*, 230, 499–507.
13. Ali, I. (2012). New generation adsorbents for water treatment. *Chemical Reviews*, 112(10), 5073–5091.
14. Sud, D., Mahajan, G., & Kaur, M. P. (2008). Agricultural waste material as potential adsorbent for sequestering heavy metals. *Bioresource Technology*, 99(14), 6017–6027.
15. Tan, I. A. W., et al. (2008). Adsorption isotherm models in environmental research. *Journal of Environmental Sciences*, 20(1), 116–122.
16. Ho, Y. S., & McKay, G. (1999). Pseudo-second order kinetic model for adsorption. *Process Biochemistry*, 34(5), 451–465.
17. Weber, W. J., & Morris, J. C. (1963). Kinetics of adsorption on carbon. *Journal of the Sanitary Engineering Division*, 89(2), 31–60.
18. Igwe, J. C., & Abia, A. A. (2006). Review of heavy metal removal using adsorbents. *Ecotoxicology and Environmental Safety*, 63(3), 402–407.
19. Vakili, M., et al. (2019). Heavy metal removal using modified bioadsorbents. *Journal of Cleaner Production*, 224, 102–115.
20. Inyang, M., et al. (2016). A review of biochar for heavy metal adsorption. *Chemosphere*, 143, 1–14.