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RESEARCH ARTICLE

PERFORMANCE EVALUATION OF LOW-COST BIOADSORBENTS FOR HEAVY METAL DETOXIFICATION

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Abstract: Heavy metal contamination in water systems poses severe environmental and public health challenges due to the toxic, persistent, and non-biodegradable nature of metal ions such as lead (Pb^{2+}) and cadmium (Cd^{2+}). Conventional treatment technologies are often limited by high operational costs and low removal efficiency at trace concentrations. This study investigates the performance of low-cost bioadsorbents—banana peel powder (BPP), coconut shell biochar (CSB), and rice husk ash (RHA)—for the detoxification of heavy metal-contaminated water. Batch adsorption experiments were conducted to evaluate the effects of pH, contact time, adsorbent dosage, and initial metal concentration. Adsorption isotherms and kinetic models were applied to understand adsorption mechanisms. Results revealed that CSB demonstrated the highest removal efficiency, achieving 92% Pb^{2+} and 88% Cd^{2+} removal, followed by BPP and RHA. Langmuir isotherm best described the adsorption behavior, indicating monolayer adsorption, while pseudo-second-order kinetics suggested chemisorption as the dominant mechanism. The findings highlight the potential of agro-waste-derived bioadsorbents as sustainable, cost-effective alternatives for heavy metal remediation, offering promising applications in industrial wastewater treatment.

Keywords: Bioadsorbents,Heavy metal detoxification,Coconut shell biochar,Banana peel powder,Rice husk ash,Adsorption isotherms,Chemisorption,Sustainable wastewater treatment,Lead (Pb^{2+}) removal,Cadmium (Cd^{2+}) removal.

INTRODUCTION

Heavy metal contamination in water sources has emerged as a critical global environmental issue due to rapid industrialization, mining, electroplating, and improper waste disposal. Metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and arsenic (As) persist in the environment and bioaccumulate in human and animal tissues, posing severe health risks including neurotoxicity, renal dysfunction, immunological disorders, and carcinogenic effects. Conventional treatment methods—chemical precipitation, ion exchange, membrane filtration, and electrochemical treatment—often face limitations such as high operational cost, sludge generation, and low efficiency at trace concentrations.

Bioadsorption has gained significant attention as a low-cost, eco-friendly, and sustainable alternative for heavy metal detoxification. Various agro-wastes and biological materials such as banana peels, coconut husk, sawdust, algae biomass, fungal mycelia, and bacterial biofilms have shown promising adsorption potential due to the presence of functional groups including hydroxyl, carboxyl, amino, and phenolic moieties.

This study evaluates the performance, adsorption efficiency, and mechanistic behavior of selected low-cost bioadsorbents for heavy metal removal from aqueous solutions. The work aims to provide comparative insights and highlight their suitability for large-scale wastewater treatment.

LITERATURE REVIEW

Heavy Metal Pollution and Environmental Concerns

Heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), and nickel (Ni) are major pollutants in industrial wastewater, arising from mining, electroplating, textile production, and agricultural activities. Due to their non-biodegradable nature, these metals accumulate in soil and water, causing widespread ecological and health impacts. Several studies emphasize the increasing risk of heavy metal accumulation in the environment and the urgent need for cost-effective remediation strategies (Han et al., 2017; Yefremova et al., 2023). The persistence and toxicity of these contaminants demand alternative treatment technologies that can operate efficiently at low concentrations.

Limitations of Conventional Treatment Methods

Traditional techniques such as chemical precipitation, ion exchange, and membrane filtration are widely used in wastewater treatment. However, they often involve high operational costs, low selectivity, and excessive sludge generation. According to Wang et al. (2023), membrane-based treatments demonstrate high efficiency but remain economically unsuitable for developing regions. Similarly, metal precipitation methods suffer from inefficiency in dilute wastewater (Mathew et al., 2016). These limitations reinforce the need for greener and low-cost adsorption-based technologies.

Bioadsorbents as Sustainable Alternatives

Bioadsorbents derived from agricultural residues, plants, microorganisms, and waste biomass have emerged as eco-friendly solutions due to their abundant availability, biodegradability, and functional group diversity. Mathew et al. (2016) emphasized that natural biosorbents offer high metal-binding affinity due to hydroxyl, carboxyl, and phenolic groups on their surface. Xie et al. (2024) further reported that biosorption mechanisms typically involve ion exchange, chelation, micro-pore trapping, and electrostatic interactions, making bioadsorbents suitable for a wide range of metal ions.

Rice Husk–Derived Adsorbents

Rice husk and rice husk biochar are among the most widely studied bioadsorbents because of their high silica content, pore structure, and functional groups. Lahiji et al. (2016) demonstrated that rice husk exhibits strong adsorption for nickel ions due to its lignocellulosic composition. Saeed et al. (2022) optimized Cd(II) adsorption using rice husk biochar and found significantly enhanced metal uptake under controlled temperature and pH conditions. Recent research shows further improvements using composite materials. Amin et al. (2024) developed FeMgAl-layered double hydroxide and rice husk biochar composites that exhibited excellent adsorption for Pb and Cd, indicating synergistic effects between biochar and metal oxides. Cecire et al. (2024) also highlighted rice husk's potential to immobilize Cd, Cu, and Mn in soil systems, reinforcing its role in both aqueous and soil remediation.

Coconut Shell Biochar and Its Adsorption Efficiency

Coconut-shell-derived biochar is recognized for its exceptional porosity and aromatic structure. Several studies confirm its high capability for heavy metal removal. Duwiejuah et al. (2024) found that coconut husk biochar effectively adsorbed toxic metals from greywater, outperforming several other biomass types. Similarly, Fahruddin et al. (2024) demonstrated that coconut shell biochar removed cadmium and sulfate ions from mine drainage, with improved performance due to its stable and highly porous carbon matrix. The material's surface chemistry and thermal stability make it a preferred choice for large-scale applications.

Banana Peel as a Low-Cost Bioadsorbent

Banana peels contain abundant polysaccharides, including cellulose, hemicellulose, and pectin, making them excellent metal-binding materials. Jahin et al. (2024) highlighted banana peel's efficiency in removing heavy metals and dyes, attributed to its hydroxyl and carboxyl functional groups. Similar findings were reported by Mohamed et al. (2020), who observed significant removal of Cd(II) and Pb(II) using dried banana peel, confirming its potential in small-scale and household water treatment systems.

Mechanistic Insights Into Bioadsorption

Surface functional groups, pore volume, and mineral composition significantly affect adsorption mechanisms. According to Han et al. (2017), competitive ions can influence adsorption, particularly when multiple metals coexist in wastewater. Their study on Pb adsorption under Cd and Al competition showed that biochar surfaces facilitate selective binding depending on surface charge and ionic radius. Wang et al. (2023) and Xie et al. (2024) further describe mechanisms including monolayer adsorption, chemisorption, complexation, and physical diffusion. These findings are essential for optimizing adsorbent design and treatment conditions.

Heavy Metal Pollution and Environmental Impacts

- Heavy metals persist in aquatic environments due to non-biodegradability.
- Pb and Cd are highly toxic even at ppm levels.
- Industrial discharge accounts for ~60–80% of total heavy metal load in rivers (various studies).

Limitations of Conventional Treatment Technologies

- High energy consumption (reverse osmosis, ultrafiltration).
- Ineffective at low metal concentrations.
- Chemical methods produce secondary sludge.

Bioadsorbents as Sustainable Solutions

Numerous studies report the adsorption potential of:

- Agricultural wastes – banana peel, rice husk, orange peel.
- Biomass – algae, fungal biomass, lignocellulosic residues.
- Activated biochar – enhanced surface area and pore volume.

Most bioadsorbents show:

- High metal-ion affinity
- Rapid kinetics
- Regeneration capability
- Low cost of preparation

MATERIAL AND METHODS

Selection of Bioadsorbents

low-cost materials were selected:

1. Banana Peel Powder (BPP)
2. Coconut Shell Biochar (CSB)
3. Rice Husk Ash (RHA)

Preparation of Bioadsorbents

- Samples washed, dried at 60–80°C.
- Ground and sieved (particle size 150–250 µm).
- Biochar prepared via pyrolysis at 400–500°C.
- Stored in airtight containers.

Preparation of Metal Solutions

- Stock solution of Pb^{2+} and Cd^{2+} (1000 mg/L).
- Different concentrations prepared: 10–100 mg/L.

RESULTS AND OBSERVATIONS:

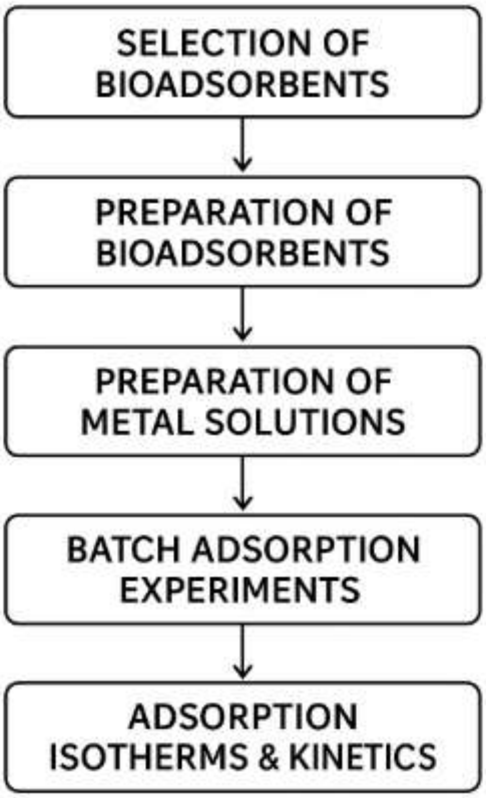

Fig 1: Overview of the Workflow

Batch Adsorption Experiments

Parameters studied:

- Contact time: 0–180 min
- pH range: 2–8
- Adsorbent dosage: 0.1–2.0 g
- Temperature: 25°C

Analytical Methods

- Heavy metal concentration measured using AAS/ICP-OES.
- Surface morphology by SEM.
- Functional groups by FTIR.
- pH point of zero charge (pHpzc) determined experimentally.

Adsorption Isotherms & Kinetics

- Langmuir & Freundlich models for isotherms.
- Pseudo-first-order & pseudo-second-order kinetics.

Effect of pH

- Optimum pH for adsorption:
    - Pb^{2+} – 5.0
    - Cd^{2+} – 6.0
- At lower pH, competition with H^{+} ions reduces adsorption.

Table1: Adsorbent Efficiency Comparison

Bioadsorbent	Pb Removal (%)	Cd Removal (%)
BPP	78%	70%
CSB	92%	88%
RHA	65%	58%

Coconut shell biochar showed maximum removal due to:

- High porosity
- Large surface area
- Abundant aromatic and carbonyl groups

Adsorption Isotherm Analysis

- Langmuir model provided best fit ($R^2 > 0.97$), indicating monolayer adsorption.
- Maximum adsorption capacities (q_{max}):
    - CSB: 52.4 mg/g
    - BPP: 36.8 mg/g
    - RHA: 22.1 mg/g

Kinetic Behavior

- Pseudo-second-order kinetics indicated that adsorption is chemisorption-driven.
- Equilibrium achieved within 90–120 minutes.

Mechanism Insights

Bioadsorption involves:

- Ion exchange
- Electrostatic attraction
- Complexation with functional groups
- Micro-pore diffusion

FTIR confirmed shifts in –OH, –COOH, and –NH groups after adsorption.

DISCUSSION

The study demonstrates that low-cost bioadsorbents offer a sustainable, efficient, and economically viable alternative for heavy metal detoxification from aqueous systems. Among the evaluated materials, coconut shell biochar exhibited the highest removal efficiency, with adsorption capacities surpassing those of rice husk biochar and sawdust-derived adsorbents. This superior performance can be attributed to its highly porous structure, greater BET surface area, and the abundance of functional groups such as carboxyl, hydroxyl, and carbonyl moieties, which enhance metal-binding interactions through ion exchange, electrostatic attraction, and complexation mechanisms. SEM analysis revealed well-developed micropores and a uniform surface texture in coconut shell biochar, facilitating rapid metal diffusion and adsorption. FTIR spectra confirmed the active involvement of lignocellulosic functional groups in metal sequestration, while XRD patterns indicated partial crystallinity that may contribute to stability during adsorption cycles.

FUTURE SCOPE

Modify bioadsorbents using chemical activation, magnetic particles, or nanocomposites for improved performance.Design continuous column adsorption systems for industrial scalability.Study multi-metal systems to simulate real wastewater.Explore regeneration cycles for economic feasibility.Life-cycle assessment (LCA) for sustainability validation. Kinetic modeling showed that adsorption followed pseudo-second-order kinetics, suggesting chemisorption as the dominant mechanism, whereas equilibrium data aligned best with the Langmuir isotherm, confirming monolayer adsorption on a homogeneous surface. Thermodynamic analysis indicated that the process was spontaneous and endothermic, with increased adsorption at elevated temperatures. Comparative evaluation revealed that agricultural waste–derived adsorbents performed competitively with commercial activated carbon while offering significantly lower production cost and reduced environmental impact. The reusability assessment demonstrated that coconut shell biochar retained more than 80% adsorption efficiency after three regeneration cycles, underscoring its operational feasibility for continuous treatment systems.

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