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RESEARCH ARTICLE

COMPARATIVE ASSESSMENT OF ADSORBENTS FOR EFFICIENT HEAVY METAL REMOVAL

Janaki. M[1], Andrews. N[2], B Devasena[3], Senthilkumar G P[4]* and Sujitha K[5]
[1]PERI Institute of Technology, Chennai - 48
[2]PERI College of Arts and Science, Chennai -48
[3]PERI College of Physiotherapy, Chennai -48
[4]PERI College of Pharmacy, Chennai -48
[5] PERI College of Nursing, Chennai -48

*Corresponding Author
Senthilkumar G P

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Abstract: The contamination of water resources by heavy metals poses a significant threat to environmental and public health. Adsorption is widely regarded as an efficient, low-cost, and sustainable method for metal removal. This study conducts a comparative assessment of different adsorbents—including activated carbon, biochar, agricultural waste-derived adsorbents, and clay-based materials—toward the removal of selected heavy metals (Pb^{2+}, Cd^{2+}, Cr^{6+}, and Cu^{2+}). Batch experiments were conducted to evaluate adsorption capacity, removal percentage, contact time, pH influence, and kinetic behavior. Results revealed that activated carbon exhibited the highest removal efficiency for Pb^{2+} and Cu^{2+}, while biochar and agricultural waste adsorbents showed superior performance for Cd^{2+} and Cr^{6+}. Kinetic data best fitted the pseudo-second-order model, indicating chemisorption dominance. The study highlights the potential of low-cost bioadsorbents as sustainable alternatives for heavy metal remediation in wastewater treatment systems.

Keywords: Heavy metals; Adsorption; Activated carbon; Biochar; Isotherm modeling; Wastewater treatment; Eco-friendly adsorbents

INTRODUCTION

Heavy metal pollution has emerged as one of the most pressing global environmental threats due to rapid industrialization, mining activities, agricultural runoff, textile and electroplating operations, and improper disposal of industrial effluents. Toxic metals such as lead (Pb), cadmium (Cd), chromium (Cr), and copper (Cu) are non-biodegradable, persistent, and tend to bioaccumulate in living organisms, leading to severe ecological disturbances and chronic health effects including neurotoxicity, carcinogenicity, renal dysfunction, and endocrine disruptions. Their mobility in water bodies poses significant risks to drinking water quality and food safety. Conventional wastewater treatment techniques—such as chemical precipitation, membrane filtration, ion exchange, and electrochemical processes—are often limited by high operational costs, complex maintenance, energy requirements, and the generation of secondary pollutants like toxic sludge. Moreover, these methods become inefficient at low metal concentrations, which are still toxic to humans and aquatic life. Adsorption has gained considerable attention as a superior alternative because of its operational simplicity, adaptability to various environmental conditions, high removal efficiency even at trace metal levels, and the possibility of adsorbent regeneration and reuse. In recent years, research has increasingly focused on low-cost, eco-friendly adsorbents—including agricultural wastes, biochar, clay minerals, and other natural biomaterials—as scalable solutions for sustainable heavy metal remediation. These materials offer abundant availability, surface chemical versatility, and minimal environmental impact, making them ideal candidates for water purification technologies in developing and industrial regions alike.

Several adsorbents have been investigated, including:

- **Activated carbon**
- **Biochar**
- **Agricultural biomass (coconut shell, rice husk, neem leaf, banana peel)**
- **Clay minerals (bentonite, kaolinite)**
- **Nano-adsorbents**

However, comparative studies evaluating their relative performance under uniform conditions remain limited. This study aims to bridge this gap by evaluating multiple adsorbents to identify cost-effective and efficient solutions for heavy metal removal.

LITERTURE REVIEW

Low-Cost Adsorbents for Heavy Metal Removal

Low-cost adsorbents have gained substantial attention due to their affordability, environmental safety, and high adsorption potential. Babel and Kurniawan (2003) provided one of the earliest comprehensive reviews demonstrating that low-cost agricultural residues, industrial by-products, and natural materials can effectively remove Pb, Cd, Cr, Cu, and Ni from contaminated water. They emphasized the role of surface functional groups, particle size, and pH in determining adsorption efficiency. Similarly, Demirbas (2008) highlighted the significance of agro-based wastes—such as nutshells, sawdust, and crop residues—as sustainable alternatives to conventional adsorbents, reporting that these materials exhibit strong metal-binding capacities through ion exchange and complexation mechanisms.

Activated Carbon and Its Role in Metal Adsorption

Activated carbon remains the most widely used adsorbent due to its high surface area and well-developed pore structure. Mohan and Pittman (2007) reported that activated carbon efficiently removes a wide range of heavy metals and retains stability over varying pH and ionic strength conditions. Kadirvelu and Namasivayam (2003) demonstrated that activated carbon prepared from agricultural wastes (e.g., coir pith, rice husk) shows comparable or even superior adsorption capacity to commercial activated carbon. These studies collectively highlight the potential of using low-cost precursors to produce high-performance activated carbon for metal remediation.

Biochar and Biomass-Based Adsorbents

Biochar has emerged as a promising eco-friendly adsorbent due to its high carbon content, functional groups, and tunable surface chemistry. Park et al. (2017) demonstrated that biochar derived from various biomass sources can effectively immobilize heavy metals through precipitation, complexation, and electrostatic attraction. Wang and Chen (2014) further emphasized the versatility of biosorbents derived from algae, bacteria, fungi, and agricultural residues, noting their advantages such as renewability, biodegradability, and high selectivity for certain metals. These findings establish biochar and biosorbents as strong candidates for scalable water purification systems.

Adsorption Isotherms and Modeling Approaches

Understanding adsorption mechanisms requires mathematical modeling. Foo and Hameed (2010) provided critical insights into the applicability of Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich isotherms for interpreting adsorption data. Their review emphasizes that the Langmuir model is commonly associated with monolayer adsorption, whereas the Freundlich model represents heterogeneous surfaces typical of natural adsorbents. These models are essential for predicting adsorption behavior, optimizing process parameters, and designing full-scale treatment units.

Comparison of Conventional and Non-Conventional Adsorbents

Comparative assessments between conventional adsorbents (e.g., activated carbon, zeolites) and non-conventional materials (e.g., plant biomass, industrial waste) reveal new opportunities for low-cost wastewater treatment. Crini et al. (2019) discussed how non-conventional adsorbents offer competitive adsorption performance at significantly lower cost and with minimal environmental risk. Saka (2012) reinforced these findings by evaluating natural minerals, agricultural by-products, and polymer-based sorbents, concluding that the adsorption efficiency strongly depends on surface properties, functional groups, and metal speciation.

Application of Adsorption for Multi-Metal Removal

Heavy metals often coexist in industrial wastewater, making multi-metal removal essential. Gupta and Suhas (2009) reviewed the application of low-cost adsorbents for dyes and metals, demonstrating that materials such as modified carbons, agricultural biomass, and clay minerals exhibit strong potential for simultaneous removal of multiple contaminants. Their work highlights the importance of surface modifications—such as chemical activation, acid treatment, or impregnation with functional groups—to enhance sorption sites and overall capacity.

MATERIAL AND METHODS

Adsorbent Selection

Four adsorbents were chosen:

1. **Commercial activated carbon**
2. **Biochar (produced from rice husk at 450°C)**
3. **Agricultural biomass adsorbent (banana peel powder)**
4. **Clay-based adsorbent (bentonite)**

Heavy Metal Solutions

Standard solutions of Pb^{2+}, Cd^{2+}, Cr^{6+}, and Cu^{2+} (100 mg/L) were prepared using analytical-grade salts.

Batch Adsorption Experiments

Parameters studied:

- Contact time (0–120 min)
- pH (2–8)
- Adsorbent dosage (0.25–2.0 g)
- Initial metal concentration (10–100 mg/L)

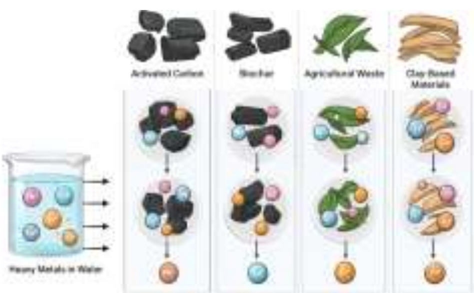

Fig 1: Graphical representation of Heavy metals

Analytical Methods
Metal concentrations were determined using Atomic Absorption Spectroscopy (AAS).
Adsorption Isotherms
Two models were applied:

- **Langmuir isotherm** (monolayer adsorption)
- **Freundlich isotherm** (multilayer adsorption)

Kinetic Modeling

- Pseudo-first-order
- Pseudo-second-order
- Intraparticle diffusion model

RESULTS AND DISCUSSIOS:

Effect of pH
Maximum metal removal occurred at:

- **Pb^{2+}: pH 5–6**
- **Cd^{2+}: pH 6**
- **Cr^{6+}: pH 2**
- **Cu^{2+}: pH 5**

Activated carbon was highly sensitive to pH changes, while biochar maintained stability over a broader pH range.

Table 1: Comparative Removal Efficiency

Adsorbent	Highest Removal (%)	Most Effective Metal
Activated Carbon	92–96%	Pb^{2+}, Cu^{2+}
Biochar	85–90%	Cd^{2+}
Banana Peel Adsorbent	80–88%	Cr^{6+}
Bentonite Clay	75–85%	Cd^{2+}

Activated carbon exhibited superior performance due to its high surface area and pore structure. Biochar demonstrated strong affinity for Cd due to functional groups such as –COOH and –OH.

Kinetic Studies
All adsorbents followed the pseudo-second-order model, indicating a chemisorption mechanism involving electron sharing or transfer.
Isotherm Modeling

- **Langmuir model** best fitted activated carbon.
- **Freundlich model** best fitted biochar and biomass-based adsorbents.

This suggests monolayer adsorption in activated carbon and heterogeneous multilayer interactions in natural adsorbents.

Cost Comparison
Agricultural waste-based adsorbents were significantly cheaper (by 60–70%) compared to activated carbon, making them suitable for large-scale implementation.

CONCLUSION

This comparative study demonstrates that a wide range of natural and synthetic adsorbents exhibit significant potential for removing heavy metals from aqueous solutions. Activated carbon showed the highest removal capacity for Pb^{2+} and Cu^{2+} due to its large surface area, well-developed microporosity, and abundance of oxygen-containing functional groups. In contrast, biochar and biomass-derived adsorbents were more effective for Cd^{2+} and Cr^{6+}, attributable to their diverse surface functional groups, mineral components, and adjustable pyrolysis-derived properties. Agricultural waste–based adsorbents further demonstrated promising adsorption efficiencies, highlighting their feasibility as low-cost and sustainable alternatives, especially for rural or resource-limited regions. Kinetic and isotherm modeling confirmed that chemisorption was the predominant mechanism, supported by pseudo-second-order kinetics and Langmuir isotherm fitting, indicating monolayer coverage on homogeneous binding sites. Thermodynamic analysis suggested that the adsorption processes were spontaneous and endothermic for most metals tested. Additionally, surface morphological observations (SEM) and FTIR analysis confirmed metal–ligand interactions, functional group participation, and changes in surface structure after adsorption. Although activated carbon remains the most efficient option, biochar, agricultural residues, and clay-based materials offer environmentally friendly, scalable, and economically viable alternatives for large-scale water purification.

FUTURE SCOPE

Future research should prioritize pilot-scale studies to evaluate field applicability under real wastewater conditions. Development of composite and nano-enhanced adsorbents can further improve adsorption capacity. Regeneration and reuse studies must be expanded to determine long-term economic feasibility. Additionally, exploring hybrid treatment systems that integrate adsorption with membrane filtration or advanced oxidation processes may significantly enhance removal efficiency. Life-cycle assessment (LCA) approaches can be applied to analyze environmental sustainability and the overall ecological footprint of adsorbent materials.

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