Efficacy Analysis of Low-Cost Natural Adsorbents for The Removal of Heavy Metals from Rural Wastewater Inflow

Dr. Magar Appasaheb Shinde[1], Mr. Sandeep Madhukar Sanap[2], Miss. Mohini Bhagwat Aghav[3]
[1]*Professor, Department of Science / Chemistry, Kasturba Gandhi Mahila Mahavidyalaya, Shirur Kasar, Beed, Maharashtra, India*
[2]*Assistant Professor, Department of Science / Microbiology, Kasturba Gandhi Mahila Mahavidyalaya, Shirur Kasar, Beed, Maharashtra, India*
[3]*Assistant Professor, Department of Science / Botany, Kasturba Gandhi Mahila Mahavidyalaya, Shirur Kasar, Beed, Maharashtra, India*

***Abstract*—Industrial expansion and modern agricultural practices have led to an increase in heavy metal pollution in water resources, threatening ecosystems and human health. Conventional treatment methods are often economically unviable for rural and semi-urban educational or domestic setups. This study systematically investigates the efficacy of low-cost, locally sourced bio-adsorbents—specifically activated carbon derived from Azadirachta indica (Neem) bark and Musa acuminata (Banana) peels—for the removal of Lead (Pb2+) and Cadmium (Cd2+) from simulated rural wastewater. Batch adsorption experiments were executed to evaluate the effects of contact time, adsorbent dosage, and pH variations. The empirical data demonstrated that Azadirachta indica bark carbon achieved a maximum removal efficiency of 92.4% for Lead at an optimal pH of 6.0, while Musa acuminata peel powder exhibited a 87.6% removal efficiency for Cadmium. The adsorption processes adhered closely to the Langmuir isotherm model, indicating monolayer binding on a homogenous surface. The findings confirm that utilizing indigenous local flora provides an eco-friendly and cost-effective matrix for decentralized small-scale wastewater treatment systems in regions like Shirur Kasar.**

***Index Terms*—Bio-adsorption, Heavy Metals, Wastewater Treatment, Langmuir Isotherm, Shirur Kasar, Environmental Science.**

I. INTRODUCTION

Rapid demographic expansion combined with intensive modern agricultural methodologies has resulted in a critical accumulation of inorganic pollutants within aquatic ecosystems. Among these pollutants, heavy metal ions such as Lead (Pb2+), Cadmium (Cd2+), and Chromium (Cr3+) represent a major environmental hazard due to their high toxicity, persistent nature, and tendency to bioaccumulate across the trophic chain. Unlike organic waste compounds, heavy metal ions cannot be biologically broken down into harmless end-products, necessitating advanced separation techniques before wastewater is discharged into natural bodies.

In localized rural sectors like Shirur Kasar within the Beed district of Maharashtra, setup and operational maintenance costs prevent the deployment of standard industrial purification systems such as ion-exchange chromatography, membrane filtration, or reverse osmosis. Consequently, developing decentralized, low-cost alternative purification matrices using agricultural waste or abundant local flora has become a primary focus in applied environmental science.

Bio-adsorption utilizes passive physical or chemical binding to accumulate metal ions on the surface of dead biomass. The cell walls of agricultural waste materials contain rich functional groups like hydroxyl, carboxyl, amino, and phosphate segments, which can chemically interact with dissolved metallic cations. This collaborative study conducted at Kasturba Gandhi Mahila Mahavidyalaya focuses on quantifying and comparing the adsorption profiles of Azadirachta indica (Neem) bark and Musa acuminata (Banana) peels to establish an economically viable wastewater treatment model for regional rural applications.

II. MATERIALS AND METHODS

A. Processing of Bio-Adsorbents

The raw biomaterials (Azadirachta indica bark and Musa acuminata peels) were gathered locally from the eco-zones of Shirur Kasar.

1) Neem Bark Carbon (NBC):
Collected bark fragments were washed extensively with deionized water to eliminate sand particles and soluble color compounds, shade-dried for 120 hours, and carbonized in a muffle furnace at 450°C for 3 hours. The resulting carbon matrix was chemically activated using 0.1 M H_3PO_4, rinsed until it reached a neutral pH, dried at 105°C, and crushed to a mesh size below 150 µm.

2) Banana Peel Powder (BPP):
Banana peels were cut into small segments, dried at 80°C in a hot-air oven for 48 hours to eliminate moisture, and pulverized mechanically without chemical carbonization to evaluate its raw functional group affinity.

B. Preparation of Synthetic Wastewater Stock

Standard stock solutions (1000 mg/L) of Lead and Cadmium were prepared by dissolving precise analytical-grade quantities of Lead Nitrate [$Pb(NO_3)_2$] and Cadmium Nitrate [$Cd(NO_3)_2 \cdot 4H_2O$] in double-distilled water containing 1 mL of concentrated HNO_3 to prevent hydrolysis. Experimental working concentrations (10 to 50 mg/L) were obtained by adding calculated volumes of distilled water to the stock solution.

C. Batch Adsorption Experiments

Adsorption trials were conducted in 250 mL Erlenmeyer flasks containing 100 mL of the simulated metal solution at a controlled agitation rate of 150 rpm on a rotary shaker. The effect of solution pH was analyzed across a range of 2.0 to 8.0, adjusted using 0.1 M HCl or 0.1 M NaOH. Adsorbent dosage parameters were varied from 0.2 g/100 mL to 1.5 g/100 mL. Upon reaching target equilibrium contact times, the samples were filtered through Whatman No. 42 filter paper. Residual heavy metal concentrations were quantified using an Atomic Absorption Spectrophotometer (AAS).
The percentage removal efficiency (R%) was calculated via the standard equation: $R\% = [(C_0 - C_e) / C_0] \times 100$, where C_0 represents the initial ion concentration (mg/L) and C_e represents the equilibrium metal ion concentration in the filtrate layer.

III. RESULTS AND DATA REPRESENTATION

The equilibrium adsorption metrics showed a high dependence on solution pH and adsorbent mass dosage. Table I outlines the shifting removal efficiencies at an initial concentration of 20 mg/L over a fixed contact period of 60 minutes.

Adsorbent Type	Target Metal	Optimal pH	Optimal Dosage (g/100mL)	Equilibrium Conc Ce (mg/L)	Max Removal Efficiency (R%)
NBC	Pb^{2+}	6.0	1.0	1.52	92.4%
NBC	Cd^{2+}	6.0	1.0	3.10	84.5%
BPP	Pb^{2+}	5.5	1.2	4.02	79.9%
BPP	Cd^{2+}	5.5	1.2	2.48	87.6%

IV. DISCUSSION

The experimental data confirms that solution pH plays a major role in governing the biosorption process. At highly acidic states (pH less than 3.0), the high concentration of Hydronium ions (H_3O^+) competes with the divalent metal cations (Pb^{2+} and Cd^{2+}) for binding sites on the adsorbent surface, resulting in low initial removal rates. As the pH increases toward a moderate range (5.5 to 6.0), the negative charge density on the cell-wall ligands increases, facilitating stronger electrostatic attraction and higher removal efficiencies.
The superior performance of Neem Bark Carbon (NBC) for Lead removal (92.4%) can be attributed to the thermal carbonization process, which significantly increases the surface area and pore volume per unit mass compared to the raw Banana Peel Powder (BPP). However, BPP showed a high affinity for Cadmium ions (87.6%), indicating that its raw pectin and

cellulose structures contain highly specific functional groups that match the ionic radius and binding characteristics of Cadmium. Fitting the equilibrium data to the Langmuir isotherm equations yielded high correlation coefficients (R2 > 0.98), confirming that adsorption occurs via uniform monolayer binding across a homogenous surface distribution.

V. CONCLUSION AND FUTURE SCOPE

This joint scientific investigation by the faculty members at Kasturba Gandhi Mahila Mahavidyalaya demonstrates that locally sourced agricultural waste and flora from the Shirur Kasar region can be successfully repurposed as high-efficiency bio-adsorbents. This approach provides a practical alternative to expensive commercial synthetic water filters.

The developed model offers an eco-friendly and economically sustainable approach for treating small-scale domestic and academic wastewater inflows. Future research phases will focus on fixed-bed continuous flow column studies to simulate real-world municipal processing constraints and evaluate regeneration protocols using mild acid eluent washes.

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