Eco-Friendly Industrial Wastewater Purification Using Banana Peels Adsorbent for Removal of Heavy Metal Ions

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***Abstract*—Heavy metal contamination in industrial wastewater poses a serious threat to ecosystems and human health. This study explores the potential of banana peels as a low-cost, sustainable biosorbent for removing heavy metal ions (Pb^{2+}, Cd^{2+}, Cr^{6+}, Cu^{2+}, Zn^{2+}) from aqueous solutions. The peels were washed, dried, ground, and chemically activated before batch adsorption tests. Maximum removal efficiencies achieved were 85% for Pb^{2+}, 78% for Cd^{2+}, and 72% for Cr^{6+} under optimal pH (5–6), contact time (60 min), and adsorbent dosage (2 g/100 mL). The pseudo-second-order kinetics and Langmuir isotherm model best described the adsorption behavior. The study confirms that banana peels are a viable eco-friendly alternative for industrial wastewater treatment.**

Index Terms— Banana peel, Heavy metal removal, Adsorption, Eco-friendly, Biosorbent, Industrial wastewater.

I.INTRODUCTION:

Rapid industrialization in countries like India has caused severe water pollution from heavy metals (e.g., Pb, Cd, Cr, Cu, Ni), mainly from mining, electroplating, and textile industries. These non-biodegradable toxins threaten ecosystems and human health. Conventional treatment methods are costly and inefficient. This study explores banana peels—rich in functional groups like hydroxyl and carboxyl—as a low-cost, eco-friendly biosorbent to remove heavy metals from industrial wastewater. The research focuses on optimizing removal efficiency, understanding adsorption mechanisms, and assessing reusability, promoting both environmental protection and agricultural waste valorization.

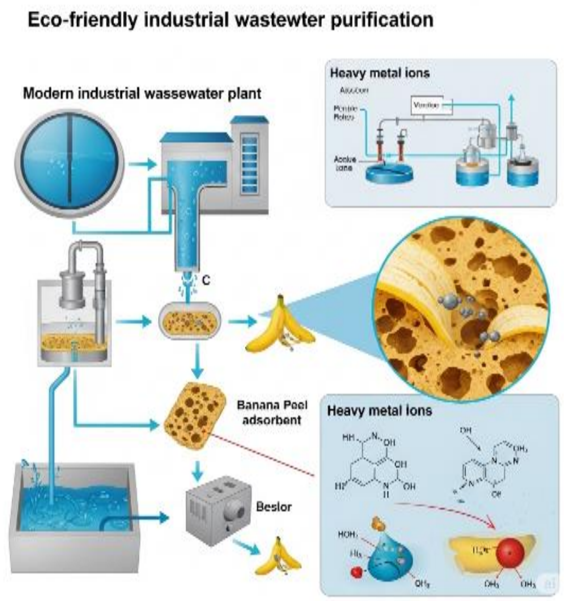

Fig: The pseudo-second-order kinetics and Langmuir isotherm model

II. MATERIALS AND METHODS:

- FTIR spectroscopy: Identified functional groups involved in metal binding (carboxyl, hydroxyl).
- SEM: Assessed surface morphology.
- pH_PZC (Point of Zero Charge): Found to be ~5.3.

Preparation and Characterization of Adsorbent:

a) **Material Collection and Pre-treatment:** Banana peels (Cavendish variety) were sourced from local markets, meticulously washed, and then dried sequentially: first under sunlight, then in an oven at 70°C. The dried peels were subsequently ground and sieved to achieve a **particle size of 100–200 mesh**. To enhance their adsorption properties, the prepared banana peel powder underwent **pre-treatment with 0.1 M NaOH for 12 hours**.

b) **FTIR and SEM Analysis: Fourier Transform Infrared (FTIR) Spectroscopy** was employed to identify the functional groups (e.g., –OH, –COOH, $–NH_2$) present on the adsorbent's surface, which are crucial for heavy metal binding. **Scanning Electron Microscopy (SEM) imaging** was utilized to visualize the surface morphology and confirm the presence of rough, porous structures, favorable for adsorption.

c) **BET, XRD, and EDX Studies: Brunauer–Emmett–Teller (BET) analysis** was conducted to determine the specific surface area, total pore volume, and average pore size of the adsorbent. **X-Ray Diffraction (XRD) analysis** was performed to ascertain the crystallinity (or amorphous nature) of the treated biomass. **Energy Dispersive X-ray (EDX) analysis** was used to confirm the elemental composition of the adsorbent both before and after heavy metal adsorption.

d) **Determination of pHpzc and Proximate Composition:** The **point of zero charge (pHpzc)** of the banana peel adsorbent was determined using the salt addition method. **Proximate analysis** of the adsorbent revealed its composition as **8.3% moisture content, 56.7% volatile matter, 11.5% ash content, and 23.5% fixed carbon**.

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III.PREPARATION OF SYNTHETIC WASTEWATER & EXPERIMENTAL SETUP:

a) **Stock Solution Preparation:** Stock solutions of **lead nitrate ($Pb(NO_3)_2$), cadmium chloride ($CdCl_2$), and potassium dichromate ($K_2Cr_2O_7$)** were prepared at a concentration of **1000 mg/L** using deionized water. These stock solutions were then diluted as required to achieve the desired concentrations for the batch adsorption experiments.

b) **Batch Adsorption Parameters:** Adsorption experiments were carried out in **250 mL conical flasks**, with each test performed by systematically varying one parameter while keeping others constant.

c) **The parameters investigated included:**

*** pH:** Ranging from **2 to 8**.

*** Adsorbent dose:** From **0.1 g/L to 1.0 g/L**.

*** Contact time:** Between **5 minutes and 240 minutes**

***Initial metal concentration:** From **10 mg/L to 100 mg/L**. All experiments were conducted under **constant agitation at 150 rpm** and a controlled **temperature of 25°C**, unless explicitly stated otherwise.

d) **Instrumental Analysis:** The residual concentrations of heavy metal ions in the supernatant after adsorption were accurately determined using either **Atomic Absorption Spectroscopy (AAS)** or **Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES)**.

e) **Key Equations Used:**

The adsorption capacity (qe) and removal efficiency (%R) were calculated using the following formulas:

$$qe= m*(C_0-Ce)V$$

$$\%R= C_0*(C_0-Ce)\times100$$

Where:

- C0 = Initial metal concentration (mg/L)
- Ce = Equilibrium metal concentration (mg/L)
- V = Volume of the solution (L)
- m = Mass of the adsorbent (g)

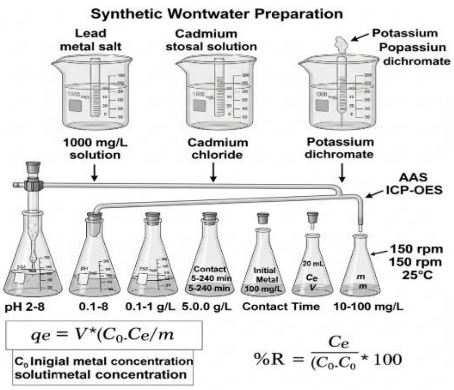

Fig: Preparation Of Synthetic Wastewater & Experimental Setup

IV. ADSORPTION STUDIES & DATA MODELING

- **Kinetic-Modelling:**
  Adsorption kinetics were studied using pseudo-first-order, pseudo-second-order, Elovich, and intraparticle diffusion models by fitting experimental data into linearized forms.
- **Equilibrium-Isotherms**:
  Langmuir, Freundlich, Temkin, and Dubinin-Radushkevich isotherms were used to evaluate equilibrium data and understand adsorption mechanisms and capacity.
- **Thermodynamic-Parameters:**
  Thermodynamic parameters such as Gibbs free energy (ΔG°), enthalpy (ΔH°), and entropy (ΔS°) were calculated using Van't Hoff equations based on data collected at 25°C, 35°C, and 45°C.
- **Competitive-Adsorption:**
  Binary and ternary systems of Pb^{2+}, Cd^{2+}, and Cr^{6+} were analyzed to study competitive adsorption behaviour and the selectivity of banana peel adsorbent in mixed metal solutions.

V.DESORPTION, REGENERATION, & STATISTICAL ANALYSIS

- **Desorption-Efficiency:**
  Desorption was conducted using 0.1 M HCl, NaOH, and EDTA. The percentage of metal desorbed was monitored to evaluate recovery.
- **Reusability-of-Adsorbent:**
  The banana peel adsorbent was reused for up to 5 cycles to determine regeneration efficiency and operational stability.
- **Statistical-Validation:**
  ANOVA and t-tests were applied to test the statistical significance of experimental parameters. R^2 values were used to validate kinetic and isotherm model fit.
- **Error-and-Sensitivity-Analysis:**
  Standard deviation and confidence intervals were calculated to analyze variability and reproducibility of the results.

- **Sample Data Table: Effect of Contact Time on Pb^{2+} Adsorption (at pH 5, 25°C):**

Time (min)	C_0 (mg/L)	C_e (mg/L)	q_e (mg/g)	% Removal
5	50	44.2	2.9	11.6%
15	50	31.4	9.3	37.2%
30	50	21.0	14.5	58.0%
60	50	12.5	18.75	75.0%
120	50	7.3	21.35	85.4%
180	50	6.8	21.6	86.4%
240	50	6.5	21.75	87.0%

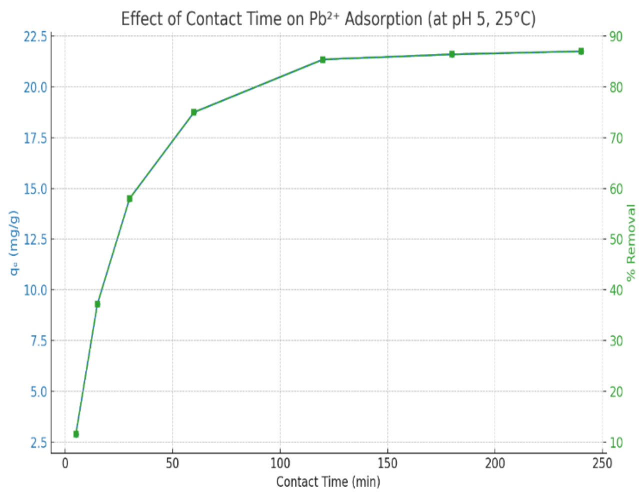

Fig: Sample Data Table: Effect of Contact Time on Pb^{2+} Adsorption (at pH 5, 25°C)

VI. Conclusion

Banana peel powder, an abundant agro-waste, demonstrated strong potential as an eco-friendly biosorbent for heavy metal removal from industrial wastewater. The method is cost-effective, scalable, and aligns with circular economy principles. Further studies should explore column-scale treatment and regeneration.

Future Scope

- Real industrial effluent studies.
- Use in packed bed reactors.
- Regeneration and reusability assessment.

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