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Removal of Pb^{2+} and Cd^{2+} from Aqueous Solutions Using Plantain (Musa paradisiaca) Stem Sap Extract

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Abstract **Original Research Article**

This study explores the potential of Musa paradisiaca (plantain) stem sap extract as a sustainable biosorbent for the removal of Pb^{2+} and Cd^{2+} from aqueous solutions. The aim was to assess its feasibility for heavy metal removal through experimental and analytical approaches. The sap extract was obtained from fresh plantain stems and the biosorbent extracted from the plantain stem sap was subjected to characterization tests to determine its physicochemical properties. These included Fourier-transform infrared spectroscopy (FTIR), solubility analysis, pH measurement, and melting point determination. Adsorption experiments using the biosorbent on an aqueous solution were conducted by varying parameters such as contact time, solution pH, and extract dosage. These tests were used to evaluate the extract's removal efficiency and adsorption behavior for Pb^{2+} and Cd^{2+} ions. Results showed the sap extract had 63.54% solubility in distilled water and a pH of 4.59. FTIR analysis revealed key functional groups such as hydroxyl, carbonyl, and amine present in the biosorbent. Maximum removal efficiencies were 98.29% for Pb^{2+} at 60 minutes and 93.59% for Cd^{2+} at 80 minutes. Pb^{2+} adsorption decreased beyond a dosage of 0.4 g, while Cd^{2+} removal improved with increasing dosage. Adsorption Isotherm modeling showed Pb^{2+} and Cd^{2+} fit the Freundlich model with R^2 of 0.9545 and 0.999 respectively, while Cd^{2+} fits the Langmuir model (R^2 = 0.9658), suggesting multilayer adsorption on heterogeneous sites. Conclusively, findings from the study demonstrated that Musa paradisiaca stem sap extract is an effective and eco-friendly biosorbent for removing Pb^{2+} and Cd^{2+} from aqueous solutions. The extract's solubility, presence of key functional groups, and favorable adsorption performance indicates its potential for sustainable heavy metal remediation.

Keywords: Musa paradisiaca; Plantain; Stem sap; Pb(II) Cd(II); Adsorption.

INTRODUCTION

Environmental pollution caused by heavy metal contamination has emerged as a pressing global concern. These persistent pollutants, originating from industrial, agricultural, and mining activities, pose severe ecological and public health risks due to their toxicity, non-biodegradability, and tendency to bioaccumulate in living organisms (Tchounwou et al., 2012; Jaishankar et al., 2014). Conventional remediation techniques such as chemical precipitation, ion exchange, and membrane filtration, though effective, are often expensive, energy-intensive, and may generate secondary pollutants. As a result, the scientific community is increasingly turning toward sustainable, low-cost, and eco-friendly alternatives for managing heavy metal pollution.

Phytoremediation, the use of plant-based systems to remove or neutralize contaminants has gained considerable traction in recent decades. Traditionally, this approach has focused on hyperaccumulator plants capable of sequestering heavy metals through their root systems. However, an emerging area of research explores the use of plant-derived extracts rich in bioactive compounds as direct agents for metal extraction and detoxification. These plant extracts, containing chelating agents such as organic acids, phenolics, and flavonoids, have shown promising potential in adsorbing and complexing heavy metals from contaminated media (Ali et al., 2013; Bharatham et al., 2021).

One such underutilized botanical resource is Musa paradisiaca, commonly known as plantain. Belonging to the Musaceae family, plantain is a staple crop in many tropical and subtropical regions, particularly in West and Central Africa, Southeast Asia, and South America (Swennen & Vuylsteke, 2001; Robinson & Sauco, 2010). While its fruit is widely consumed for its nutritional benefits, large portions of the plant—including the pseudostem—are often discarded as agricultural waste after harvest. Interestingly, the **pseudostem sap** has been traditionally used in folk medicine to treat wounds, burns, and inflammatory conditions due to its antimicrobial and coagulating properties (Akinmoladun & Akinrinlola, 2018).

Recent studies have shed light on the rich phytochemical profile of the plantain pseudostem, which includes compounds such as alkaloids, tannins, saponins, and polyphenols. These constituents exhibit strong metal-binding capabilities through mechanisms such as adsorption, ion exchange, and chelation (Ahmed et al., 2022; Ali et al., 2020). Notably, organic acids like citric and oxalic acids present in the sap enhance the solubilization and immobilization of metal ions, making plantain sap a promising candidate for environmental remediation efforts (Ekeke & Enebechi, 2021).

Despite its abundance and chemical richness, the potential of Musa paradisiaca pseudostem sap for heavy metal extraction remains underexplored. Most existing research has emphasized the nutritional or agricultural value of the plant, while its application in environmental management, particularly in aqueous metal decontamination, has received limited attention. Harnessing this overlooked resource offers dual advantages: mitigating the environmental impacts of heavy metal pollution and promoting sustainable reuse of agricultural byproducts.

This study therefore investigates the feasibility of using plantain pseudostem sap extract for the adsorption and removal of toxic heavy metals from aqueous environments. By analyzing the chemical composition of the sap, optimizing extraction parameters, and evaluating its metal-binding efficiency, this research aims to contribute to the growing body of knowledge on plant-based bioremediation and inspire scalable, green solutions to environmental contamination..

2. METHODOLOGY

2.1 Sample and Extract Preparation

Fresh plantain stems were identified and collected from the herbarium of Plant Science department, University of Port Harcourt in Rivers State, Nigeria. The outer parts of the stems were peeled off to remove any dirt, and the inside parts (leaf sheaths) were washed thoroughly with clean tap water.

After washing, the stems were left to air-dry at room temperature for a few hours. They were then cut into smaller pieces and ground into a smooth paste using a mechanical grinder. To get the extract, plantain paste was mixed with 300 mL of acetone. The mixture was filtered to remove solid parts, and the leftover pulp was mixed again with another 100 mL of acetone to get as much extract as possible. The filtered liquids were combined and heated in a water bath to remove the acetone. What was left was dried in an oven until it reached a constant weight.

2.2 Structural Elucidation and Physiochemical Properties of the Extract

2.2.1 Functional Group Identification (FTIR Analysis)

The function groups were identified by mixing 2 mg of biosorbent with potassium bromide (KBr), pressed into a thin disc, and tested using an FTIR spectrometer. The functional groups present in the extract were thus, identified.

2.2.2 Melting Point

The biosorbent was put in a capillary tube and slowly heated in a melting point apparatus (Model 934). The temperature at which it melted was recorded.

2.2.3 pH Measurement

One gram of the extract was mixed in 10 mL of distilled water, and the pH was checked with a pH meter calibrated using standard buffers. It was dipped into the mixture and the pH readings were recorded.

2.2.4 Solubility and %Solubility

For solubility test, about 0.15 g was mixed separately with 5 mL of different liquids like water, methanol, ethanol, acetone, chloroform, toluene, and hexane. Also the %Solubility was found by mixing 0.31 g of the extract in distilled water and stirred for 30 minutes, then filtered. The residual solid was dried and weighed. The %Solubility is calculated using the formula:

$$\text{Percentage Solubility } (\%) = \frac{\mathrm{W}i - \mathrm{W}f}{\mathrm{W}i} \times 100 \quad (1)$$

Where:

$\mathrm{W}i$ = initial Weight (g)
$\mathrm{W}f$ = Final Weight (g)

2.3 Preparation of the Heavy Metal Solutions

The heavy metal stock solutions were prepared by dissolving 1.597g of lead nitrate in distilled water and diluted up to 1 liter. Similarly, 1.633 g of cadmium chloride was used to make a 1-liter cadmium solution.

2.4 Adsorption Batch Study

These studies the adsorption capacity of the extract. The adsorption efficiency is determined by varying the following parameters.

2.4.1 Contact Time

0.5 g of extract was added to 20 mL of metal solution in four containers. They were shaken at 250 rpm for 20, 40, 60, and 80 minutes. After shaking, the mixtures were filtered and saved for analysis.

2.4.2 pH

Four containers, each with 0.5 g of extract and 20 mL of metal solution, were adjusted to pH 3, 5, 7, and 9 using acid or base. After shaking for 40 minutes, the mixtures were filtered.

2.4.3 Adsorbent Dosage

Different amounts of extract (0.2 g, 0.4g, 0.6g and 0.8 g) were tested in 20 mL of metal solution (kept at pH 5) and shaken for 40 minutes. After that, they were filtered for further testing.

2.5 Adsorption Performance

Adsorption efficiency of the extract were evaluated with below measurements:

2.5.1 Percentage Removal:

The amount of metal ion absorbed was quantified using the equation:

$$\%R = \frac{Ci - Cf}{Ci} \times 100 \qquad (2)$$

Where:

Ci = Initial metal concentration before adsorption (mg/L)

Cf = Final metal concentration after adsorption (mg/L)

2.5.2 Adsorption Capacity

The amount of metal ion captured per gram of extract was calculated using the formula:

$$qe = \frac{(Ci - Cf) \times V}{m} \qquad (3)$$

Where:
Ci = initial metal concentration (mg/L)

Cf = final metal concentration (mg/L)

V = volume of solution (L)

M = amount of extract used (g)

2.6 Post Absorption Analysis

The amount of lead and cadmium remaining in the water after treatment was measured using Atomic Absorption Spectrophotometer (AAS), following standard lab methods.

2.7 Adsorption Isotherm

Adsorption isotherm for the study were carried out using Langmiur and Freundlich isotherm.

2.7.1 Langmuir Model:

Assumes the extract holds onto metals in a single layer on its surface. It helps predict the maximum amount the extract can adsorb.

$$\frac{Ce}{q_e} = \frac{1}{qmaxb} + \frac{Ce}{qmax} \qquad (4)$$

Where:

Ce = equilibrium concentration of the adsorbate (mg/L)

qe = amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg/g)

qmax = maximum adsorption capacity (mg/g)

b = Langmuir constant related to the affinity of the binding sites (L/mg)

Model constants (qmax and b) were determined from the slope and intercept of the plot of $\frac{Ce}{q_e}$ versus Ce.

2.7.2 Freundlich Model:

Assumes metals stick to the extract in multiple layers and in different spots with varying strength. Its linear form is:

$$\text{Log } qe = \log K_F + \frac{1}{n} \log Ce \qquad (5)$$

Where:

KF = Freundlich constant indicative of adsorption capacity

n = heterogeneity factor (adsorption intensity)

Ce = equilibrium concentration (mg/L)

qe = amount adsorbed at equilibrium (mg/g)

The slope $\frac{1}{n}$ and intercept log K_F were obtained from a linear plot of log q_e versus log Ce

3.0 RESULTS AND DISCUSSION

3.1 Extract Physiochemical Properties

Table 1 and 2 highlights the physiochemical properties of my plantain (*Musa paradisiaca*) stem sap extract.

Table 1 Solubility properties of Biosorbent

Solvent	**Observed Solubility**
Distilled Water	Soluble (%63.54)
Chloroform	Insoluble
Methanol	Partially Soluble
Acetone	Partially Soluble
DMSO$_4$	Insoluble
Toluene	Insoluble

Table 2 Melting Point and pH of Biosorbent

Melting Point (ºC)	354 - 358
pH	4.59

3.2. Fourier Transform Infrared (FT-IR) Analysis

The FTIR spectrum of the unripe plantain (*Musa paradisiaca*) stem sap extract, as shown in Figure 1, revealed several distinct peaks indicative of functional groups commonly associated with metal binding. A broad and strong absorption band observed at 3358.89 cm^{-1} corresponds to O–H/N–H stretching vibrations, indicating the presence of hydroxyl and amine groups. These groups are known for their capacity to form complexes with metal ions (Martins et al., 2022).

Absorption bands around 3244.99 cm^{-1} and 2874.03 cm^{-1} can be attributed to C–H stretching, signifying the presence of aliphatic chains. A strong peak at 1613.99 cm^{-1} is associated with C=C stretching vibrations, typically present in alkenes or aromatic structures (Carlos et al., 2010).

The band at 1258.85 cm^{-1} corresponds to C–N stretching vibrations, indicating the presence of amines. Furthermore, peaks in the region of 1046.81–1128.78 cm^{-1} are characteristic of C–O stretching, suggesting alcohols, esters, or ethers. These oxygen- and nitrogen-containing functional groups have been widely reported as active sites in biosorption and corrosion inhibition (Bashiri & Orouji, 2015; Ezzati, 2023).

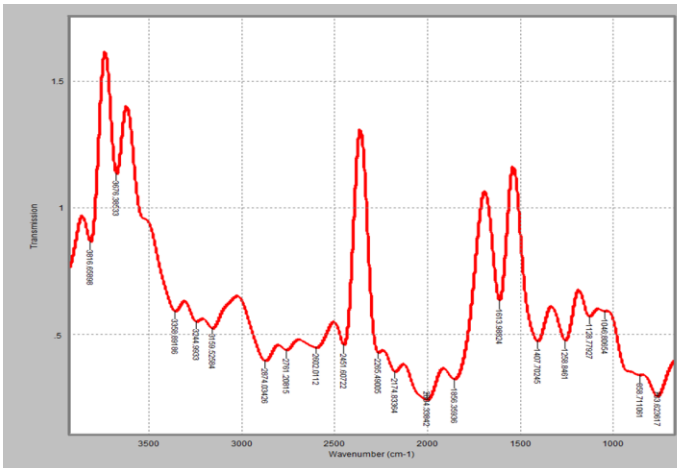

Figure 1. Musa Paradisiaca stem sap Extract FT-IR spectrum

Table 3 FTIR Peak Assignments for Extract of *Musa paradisiaca* Sap

Wavenumber (cm^{-1})	**Functional Group Assignment**	**Peak Area**
3416.616	O–H stretching (alcohols, phenols)	50.1273
2924.582	C–H stretching (alkanes)	5.63702
1637.177	C=O stretching (carbonyls, ketones)	19.4776
1381.353	C–H bending (methyl)	15.1113
1265.727	C–O stretching (carboxylic acids, esters)	10.4091
1082.372	C–O–C stretching (ethers)	8.55628
1027.760	C–N stretching (amines)	7.95023

3.3 Adsorption Batch Study

Tables 4 present the adsorption batch results of Pb (II) and Cd (II) ions onto plantain (*Musa paradisiaca*) stem sap biomass. The effects of pH, contact time, and adsorbent dosage were investigated by measuring metal removal efficiency (%R) and the equilibrium adsorption capacity (Qe). The trends are discussed below.

The effect of pH on the removal of Pb (II) and Cd (II) ions was studied over a range of 2–8 (Table 3). For Pb (II), the highest percentage removal was 68.49% at pH 2, while the lowest was 56.52% at pH 8. Interestingly, the adsorption of Pb (II) decreased with increasing pH. This trend suggests that at low pH, H^+ ions possibly facilitate the surface activation of the adsorbent, while at higher pH values, competition with metal hydroxide formation may reduce Pb^{2+} adsorption. In contrast, Cd (II) showed a more favorable response to pH increase. Its highest removal was 93.12% at pH 6, and it slightly decreased to 92.84% at pH 8, suggesting that Cd(II) adsorption is favored under near-neutral conditions, possibly due to decreased competition from H^+ ions and better ionization of functional groups on the biomass. This aligns with trends reported by Ali et al. (2020), where optimal Cd (II) removal occurred at pH 6–7. As shown in the second section of the table, Pb(II) adsorption increased significantly with time up to 60 minutes (98.29% removal), after which it declined sharply at 80 minutes (52.59%). This decline at 80 minutes could be due to desorption or saturation and restructuring of active sites, leading to diminished uptake. The Qe value also peaked at 0.5714 mg/g at 60 minutes.Cd (II) showed a gradual increase in adsorption efficiency with time, with the highest removal (93.59%) at 80 minutes, and a Qe of 1.983 mg/g. This suggests that Cd (II) adsorption reached equilibrium slower than Pb (II), likely due to differences in their ionic radii or interaction energies with active functional groups on the sap biomass.

The results in Table 4.0 show that increasing the biomass dose from 0.2 g to 0.8 g led to improved removal efficiency for both metal ions. For Pb (II), percentage removal increased from 44.00% at 0.2 g to 68.19% at 0.8 g. This improvement is attributed to the greater availability of binding sites at higher biomass concentrations, although Qe decreased due to adsorbate dilution across a higher mass of adsorbent. For Cd (II), removal rose significantly from 78.65% to 90.66%, with a corresponding decrease in Qe from 4.1681 mg/g to 1.2013 mg/g. This inverse relationship between %R and Qe is common in adsorption studies, where increased surface area facilitates adsorption but lowers the amount adsorbed per unit weight of biomass. These findings indicate that the plantain stem sap biomass demonstrates a higher affinity for Cd (II) under most experimental conditions, especially at optimal pH and longer contact times.

Table 4. Adsorption Batch study results

Effect		**Pb (II)**				**Cd (II)**			
		Co (mg/L)	**Ce (mg/L)**	**Qe**	**%R**	**Co (mg/L)**	**Ce (mg/L)**	**Qe**	**%R**
	2	13.081	4.121	0.3572	68.49	53.001	5.320	1.899	89.96
pH	**4**	13.081	4.813	0.3374	63.21	53.001	4.930	1.916	90.70
	6	13.081	4.404	0.3495	66.34	53.001	3.646	1.964	93.12
	8	13.081	5.690	0.3018	56.52	53.001	3.795	1.957	92.84
Contact Time (minutes)	**20**	13.081	4.040	0.3608	69.11	53.001	7.426	1.823	85.99
	40	13.081	1.680	0.4600	87.16	53.001	6.450	1.859	87.83
	60	13.081	0.224	0.5714	98.29	53.001	6.653	1.859	87.45
	80	13.081	6.200	0.2752	52.59	53.001	3.396	1.983	93.59
Adsorbent Dossage (g)	**0.2**	13.081	7.325	0.5756	44.00	53.001	11.320	4.1681	78.65
	0.4	13.081	5.218	0.3932	60.13	53.001	7.530	2.2736	85.80
	0.6	13.081	4.624	0.2819	64.66	53.001	5.946	1.5685	88.78
	0.8	13.081	4.160	0.2230	68.19	53.001	4.951	1.2013	90.66

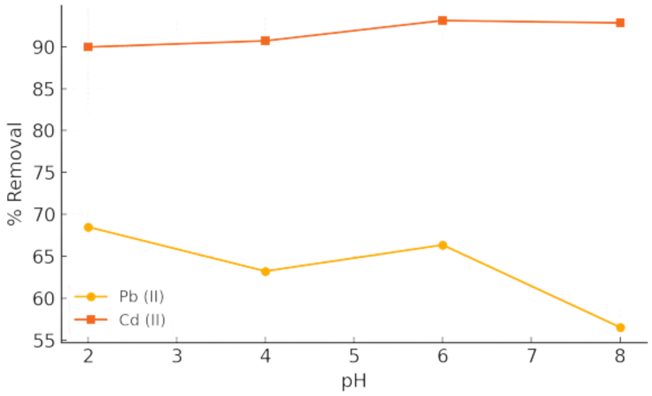

Figure 2. %Removal vs pH

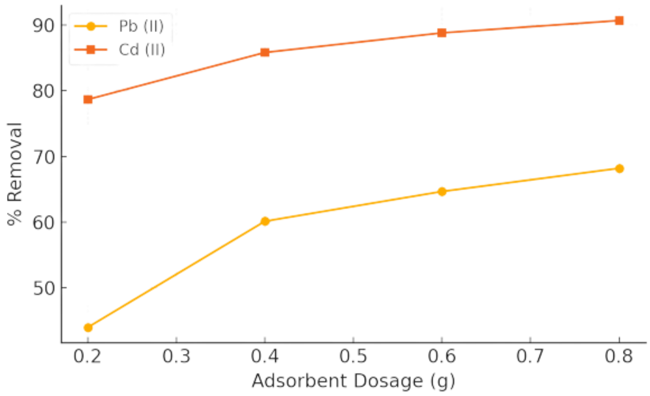

Figure 3. %Removal vs Adsorbent Dosage

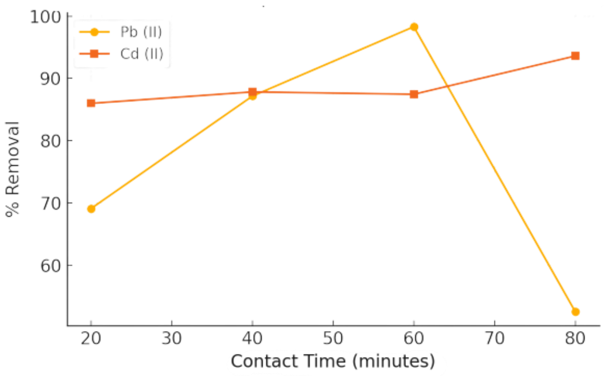

Figure 4. %Removal vs Contact Time

3.4 Adsorption Isotherm

Adsorption is the ability of the adsorbate to adhere or attach to the adsorbent. The adsorption isotherm is an equation that shows the transfer of adsorbate from aqueous phase to the adsorbent phase at equilibrium condition.

3.4.1 Langmuir Isotherm

Figure 5-6 presents the Langmuir Isotherm for biosorption of Pb (II) and Cd(II) ions onto plantain (*Musa paradisiaca*) stem sap biomass. The low R² (0.6795) supports poor model fit, suggesting that Pb^{2+} does not undergo ideal monolayer adsorption or the biosorbent surface is too heterogeneous for Langmuir assumptions. Such results are commonly reported when the adsorption is irregular or multilayered, or when there's competition among surface sites (Patiha et al., 2016; Ezzati, 2023). The values of R² (0.9658), indicate that Cd^{2+} adsorption fits well with the Langmuir model, consistent with monolayer coverage on a homogeneous surface. This confirms that the Langmuir isotherm model is more favourable to adsorption of Cd (II) onto plantain (*musa paradisiaca*) stem sap biomass.

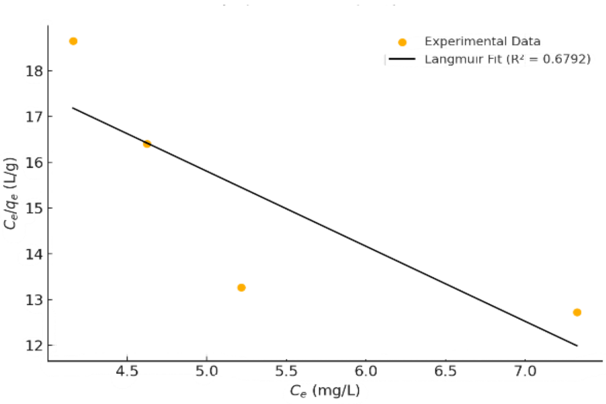

Figure 5. Langmiur Adsorption Isotherm for Pb(II)

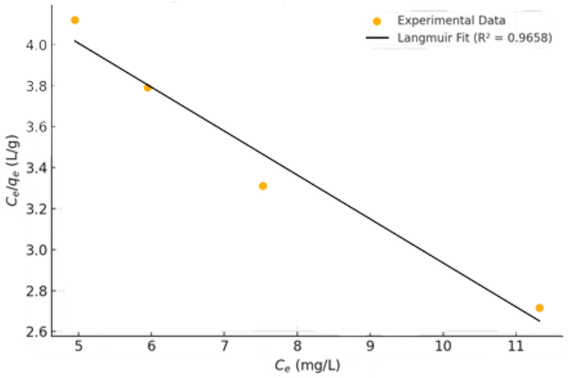

Figure 6. Langmiur Adsorption Isotherm for Cd (II)

3.4.2 Freundlich Isotherm

Figure 7 and 8 represents the Freundlich adsorption isotherm for Pb(II) and Cd(II) ions respectively.

The R^2 of 0.9545 for Pb^{2+} indicates a good fit to the Freundlich model. The value of n=0.6626 is less than 1, suggesting that adsorption is less favorable and that Pb^{2+} ions encounter some resistance or non-uniformity in available sites (Bashiri & Orouji, 2015). This supports the idea that Pb^{2+} interacts with a more complex and less uniform surface, possibly involving weak physical interactions. Cd^{2+} With a very high R^2 (0.9999) and n=1.5095 (greater than 1), reveals that Cd^{2+} adsorption is highly favorable and occurs on a heterogeneous surface. The high n value also reflects strong binding energy variation across the biosorbent surface, typical of plant-based sorbents with diverse functional groups (Carlos et al., 2010).

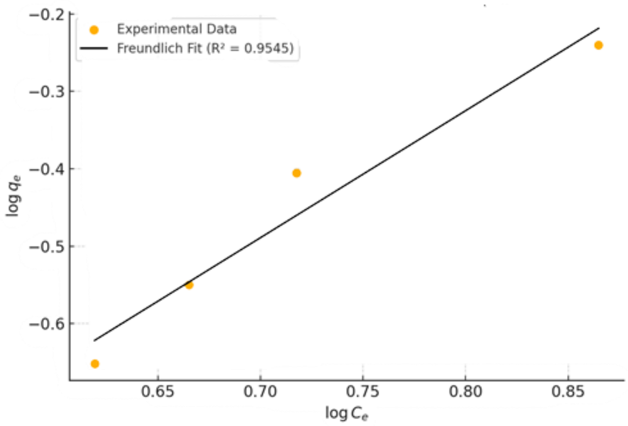

Figure 7. Freundlich Adsorption Isotherm for Pb(II)

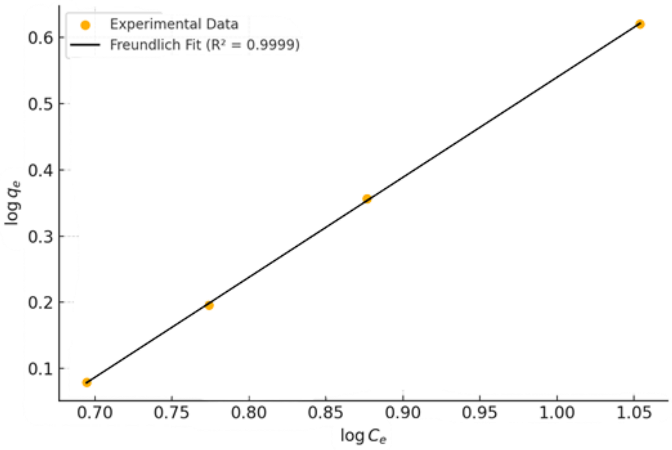

Figure 8. Freundlich Adsorption Isotherm for Cd (II)

4. CONCLUSION

The results of this study demonstrate that *Musa paradisiaca* stem sap extract possesses significant potential as a low-cost, environmentally friendly biosorbent for the removal of heavy metals, specifically lead (Pb^{2+}) and cadmium (Cd^{2+}), from aqueous environments. Comprehensive physicochemical characterization confirmed the sap's high aqueous solubility, mild acidity (pH 4.59), and thermal stability, making it suitable for practical application in diverse treatment settings. FTIR analysis revealed the presence of key functional groups such as hydroxyl, carbonyl, carboxyl, ether, and amine groups that are responsible for metal ion binding through various coordination mechanisms.

The extract exhibited effective adsorption behavior under varying operational conditions, including contact time, pH, and adsorbent dosage. Optimal removal of Pb^{2+} was observed at 60 minutes and pH 2, while Cd^{2+} removal peaked at 80 minutes and pH 6. These trends align with known metal speciation behavior and competition with hydrogen ions under acidic to near-neutral pH ranges.

Adsorption capacity (q_e) analysis revealed that lower adsorbent dosages led to higher capacity, especially for Cd^{2+} (q_e = 4.1681 mg/g at 0.2 g dosage), indicating efficient site utilization and minimal particle aggregation. This highlights the importance of dosage optimization to balance metal uptake efficiency with resource economy.

Isotherm modeling confirmed that the Freundlich model best describes the adsorption mechanism for both metal ions, particularly Cd^{2+} ($R^2 = 0.9999$), suggesting multilayer adsorption on a heterogeneous surface. In contrast, the Langmuir model provided only a moderate fit for Pb^{2+} ($R^2 = 0.6795$), further indicating that ideal monolayer adsorption assumptions were not fully met in this biosorption system. This proves that *Musa paradisiaca* sap extract is a sustainable biodegradable biosorbent for heavy metal remediation.

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