ADSORPTIVE REMOVAL OF Cd(II) FROM AQUEOUS SOLUTION USING ACTIVATED CARBON DERIVED FROM MANGO SEED COATS

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ABSTRACT

Heavy metal contamination of water systems remains a critical environmental challenge due to its persistence, toxicity and bio-accumulative nature. This study investigates the potential of activated carbon derived from mango (Mangifera indica) seed coats as a low cost and sustainable adsorbent for the removal of cadmium (Cd^{2+}) ions from aqueous solutions. The adsorbent was prepared via carbonization followed by chemical activation and characterized using Fourier Transform Infrared Spectroscopy (FTIR), which revealed the presence of functional groups such as hydroxyl and carbonyl responsible for metal binding.

Batch adsorption experiments were conducted to evaluate the effects of operational parameters, including initial metal ion concentration (10 to 50 mg/L) and adsorbent dosage (0.1 to 0.5 g) at an optimized pH of 5. The results indicated that adsorption efficiency decreased with increasing Cd^{2+} concentration, reaching a maximum removal efficiency of about 81.00 % at 10 mg/L. Furthermore, increasing adsorbent dosage beyond 0.1 g resulted in only marginal improvements due to possible site overlap and particle aggregation, identifying 0.1 g as the optimal dosage.

Equilibrium data were best described by the Freundlich isotherm model, indicating heterogeneous surface adsorption, while kinetic studies showed that the adsorption process followed pseudo second order kinetics, suggesting chemisorption as the dominant mechanism. The adsorption process was governed by electrostatic interactions, ion exchange, and surface complexation.

The study demonstrates that mango seed coat derived activated carbon is an effective, eco-friendly and economically viable alternative for Cd^{2+} removal. This work highlights the dual benefits of agricultural waste valorization and sustainable water treatment, making it particularly relevant for resource limited environments.

Keywords: Activated carbon, Mango seed coat, Cadmium removal, Adsorption, Heavy metals, Wastewater treatment, Low cost adsorbent, Biomass valorization.

INTRODUCTION

Water contamination by heavy metals has emerged as a critical global environmental issue, driven largely by rapid industrialization, urban expansion and inadequate waste management practices. Among these contaminants, cadmium (Cd(II)) is of particular concern due to its high toxicity, persistence and tendency to bio-accumulate in living organisms. Even at trace concentrations, cadmium poses severe health risks, including renal dysfunction, skeletal damage and carcinogenic effects, thereby necessitating its effective removal from contaminated water systems.

Conventional treatment technologies such as chemical precipitation, ion exchange, membrane filtration and reverse osmosis have been widely employed for heavy metal removal. However, these methods are often associated with significant drawbacks, including high operational costs, generation of secondary pollutants and reduced efficiency at low metal concentrations. In this context, adsorption has gained considerable attention as a preferred alternative due to its simplicity, cost effectiveness, high efficiency and operational flexibility.

Activated carbon remains one of the most effective adsorbents owing to its large surface area, well developed pore structure and diverse surface functional groups. Despite its excellent performance, the widespread application of commercial activated carbon is limited by its high production cost and dependence on non-renewable precursors. This limitation has driven increasing research interest toward the development of low cost, sustainable adsorbents derived from agricultural wastes.

Agricultural by-products such as coconut shells, rice husks and fruit seeds have shown significant promise as precursors for activated carbon production due to their high carbon content and inherent porosity. Among these, mango (Mangifera indica) seed coats represent an abundant and underutilized biomass resource, particularly in tropical regions. Rich in lignocellulosic components, mango seed coats can be effectively converted into activated carbon with enhanced adsorption properties through appropriate activation processes.

Recent studies have demonstrated that biomass-derived activated carbons exhibit comparable or even superior adsorption performance to commercial alternatives, particularly for the removal of heavy metals. However, further investigation is required to optimize their preparation and evaluate their efficiency under varying operational conditions.

Against this backdrop, the present study explores the adsorption potential of activated carbon prepared from mango seed coats for the removal of Cd(II) ions from aqueous solutions. By integrating waste valorization with environmental remediation, this work contributes to the development of sustainable and economically viable water treatment technologies.

Aim of the Study

The aim of this study is to develop and evaluate activated carbon derived from mango (Mangifera indica) seed coats as a low-cost and efficient adsorbent for the removal of Cd(II) ions from aqueous solutions.

Objectives of the Study

The specific objectives of this research are to:

1. Prepare activated carbon from mango seed coats using appropriate carbonization and activation methods.

2. Characterize the prepared activated carbon in terms of its surface functional groups and adsorption properties.

3. Investigate the effect of key operational parameters, including initial metal ion concentration and adsorbent dosage, on the adsorption of Cd(II).

4. Evaluate the adsorption efficiency of the prepared adsorbent using batch experimental techniques.
5. Assess the potential of mango seed coat-derived activated carbon as a cost-effective and sustainable alternative for heavy metal removal in water treatment.

LITERATURE REVIEW

Heavy metal contamination of aquatic systems has become a major global environmental challenge due to its persistence, toxicity and non-biodegradable nature. Among these pollutants, cadmium (Cd(II)) is particularly hazardous because of its high solubility, mobility and strong tendency to bio-accumulate in living organisms. Industrial activities such as electroplating, battery manufacturing, mining and fertilizer production have significantly contributed to the release of cadmium into water bodies. Exposure to Cd(II), even at trace levels, is associated with severe health effects, including kidney dysfunction, skeletal damage and carcinogenic risks, thereby necessitating the development of effective and sustainable remediation strategies.

Various conventional methods, including chemical precipitation, ion exchange, membrane filtration and reverse osmosis, have been employed for the removal of heavy metals from wastewater. However, these techniques are often limited by high operational costs, energy requirements, and the generation of secondary pollutants such as sludge. These limitations have led to increased research interest in adsorption as a more efficient and economically viable alternative. Adsorption is widely recognized for its simplicity, high efficiency, and flexibility in operation, particularly for the removal of trace-level contaminants. The process involves the accumulation of metal ions onto the surface of an adsorbent through physical and chemical interactions, which may include electrostatic attraction, ion exchange, and surface complexation.

The effectiveness of adsorption systems is typically evaluated using equilibrium isotherm and kinetic models. The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface with finite adsorption sites, whereas the Freundlich isotherm describes multilayer adsorption on heterogeneous surfaces. In many cases involving biomass-derived adsorbents, the Freundlich model provides a better representation due to the inherent surface heterogeneity of such materials. Kinetic studies often indicate that the adsorption of heavy metals follows a pseudo-second-order model, suggesting that chemisorption involving valence forces and electron sharing plays a dominant role in the adsorption mechanism.

Activated carbon is widely regarded as one of the most effective adsorbents due to its large surface area, well-developed pore structure, and abundance of functional groups capable of binding metal ions. These characteristics enable activated carbon to remove a wide range of pollutants through mechanisms such as pore filling, ion exchange, and chemical interaction with surface functional groups. Despite its effectiveness, the application of commercial activated carbon is constrained by its high production cost and reliance on non-renewable raw materials such as coal and petroleum-based precursors. Consequently, there has been a growing interest in developing low-cost and sustainable alternatives derived from agricultural wastes.

Agricultural by-products such as coconut shells, rice husks, banana peels, and fruit seeds have been extensively investigated as potential precursors for activated carbon production. These materials are rich in lignocellulosic components, including cellulose, hemicellulose, and lignin, which facilitate the formation of porous carbon structures upon carbonization and activation. Among these, mango (Mangifera indica) seed coats have emerged as a promising and underutilized biomass resource, particularly in tropical regions where mango consumption generates large quantities of waste. The high carbon content and inherent porosity of mango seed coats make them suitable for the production of activated carbon with enhanced adsorption properties.

Several studies have demonstrated the effectiveness of mango seed-derived adsorbents in the removal of heavy metals from aqueous solutions. The adsorption performance is largely attributed to the presence of surface functional groups such as hydroxyl, carboxyl, and carbonyl groups, which facilitate metal binding through complexation and ion exchange mechanisms. In addition, the porous structure of the activated carbon enhances diffusion and accessibility of metal ions to active adsorption sites. Experimental studies have reported high adsorption capacities for Cd(II) and other heavy metals, confirming the strong affinity between mango seed-based adsorbents and metal ions. The adsorption process is also influenced by various parameters, including pH, contact time, adsorbent dosage, and initial metal concentration, with optimal performance typically observed at moderately acidic to neutral pH conditions.

The method of activation plays a crucial role in determining the physicochemical properties and adsorption performance of activated carbon. Physical activation involves high-temperature treatment with oxidizing gases such as steam or carbon dioxide, while chemical activation employs activating agents such as potassium hydroxide, phosphoric acid, or zinc chloride. Chemical activation is generally preferred for biomass-derived materials due to its ability to produce higher surface area, improved pore structure, and enhanced surface functionality at relatively lower temperatures. Studies have shown that chemically activated mango seed carbon exhibits superior adsorption performance compared to physically activated counterparts, primarily due to the increased availability of active sites and functional groups.

The adsorption of Cd(II) onto biomass-derived activated carbon is governed by multiple mechanisms, including electrostatic attraction between positively charged metal ions and negatively charged adsorbent surfaces, ion exchange processes, and chemical complexation with functional groups. In many systems, these mechanisms occur simultaneously, contributing to the overall adsorption efficiency. Thermodynamic studies often indicate that the adsorption process is spontaneous and, in some cases, endothermic, suggesting improved adsorption capacity at elevated temperatures.

Despite the promising potential of mango seed-derived activated carbon, several challenges and research gaps remain. Most existing studies have been conducted under controlled laboratory conditions using single-metal systems, which do not fully represent the complexity of real wastewater containing multiple competing ions. Additionally, there is limited research on large-scale applications, continuous flow systems, and long-term adsorbent stability and regeneration. Variations in raw material composition and activation conditions also pose challenges in achieving consistent performance.

Future research should focus on evaluating the performance of mango seed-based adsorbents in multi-component systems, optimizing regeneration and reuse processes, and scaling up production for industrial applications. Furthermore, economic and life-cycle assessments are necessary to establish the feasibility and sustainability of these materials in practical water treatment systems.

MATERIALS AND METHODS

Materials

All chemicals used in this study were of analytical grade and were used without further purification. Distilled water was used throughout the experiment for solution preparation and dilution.

The primary adsorbate used was cadmium in the form of cadmium nitrate ($Cd(NO_3)_2$), which served as the source of Cd(II) ions. Other reagents included hydrochloric acid (HCl) and sodium hydroxide (NaOH), which were used for pH adjustment during the adsorption experiments.

Mango seed coats were collected locally and used as the raw material for the preparation of activated carbon.

Preparation of Activated Carbon

The mango seed coats were first washed with distilled water to remove dirt and soluble impurities, followed by drying at room temperature and further oven-drying at 105 °C to eliminate moisture content. The dried material was then crushed and sieved to obtain a uniform particle size.

Carbonization was carried out by heating the prepared biomass in a muffle furnace under limited oxygen conditions at an elevated temperature (typically between 400 °C–600 °C) for a specified duration. The resulting char was allowed to cool to room temperature.

Chemical activation was subsequently performed using a suitable activating agent (Orthophosphoric acid), H_3PO_4, to enhance porosity and surface functionality. The impregnated sample was heated at 600 °C for 90 minutes, after which it was washed repeatedly with distilled water to remove residual chemicals until a neutral pH was achieved. The final product was dried, ground, and stored in airtight containers for subsequent characterization and adsorption experiments.

Figure 1: Freshly Washed Mango Seed Coats

Figure 2: Dried Mango Seed Coats

Characterization of the Adsorbent

The surface functional groups present on the prepared activated carbon were analyzed using Fourier Transform Infrared Spectroscopy (FTIR). This technique was employed to identify key functional groups responsible for metal ion binding.

Preparation of Cd(II) Solutions

Stock solution of Cd(II) ions was prepared by dissolving accurate quantity of cadmium nitrate ($Cd(NO_3)_2$) in distilled water to obtain a concentration of 1000 mg/L for the metal ion. The stock solution serves as the primary source for preparing working solutions of desired concentrations. From the stock, working solutions ranging between 10 mg/L and 50 mg/L were prepared by serial dilution using distilled water. The pH of each solution was adjusted using either 0.1 M HCl or 0.1 M NaOH, depending on the experimental requirement. The prepared metal ion solutions were stored in polyethylene bottles and labeled accordingly to prevent contamination. All solutions were freshly prepared and used within 24 hours to avoid hydrolysis or oxidation of metal ions.

Batch Adsorption Experiments

Batch adsorption studies were conducted to evaluate the removal efficiency of Cd(II) ions using the prepared activated carbon. A known mass of adsorbent (0.1–0.5 g) was added to a series of conical flasks containing a fixed volume of Cd(II) solution of known concentration.

The pH of the solution was maintained at approximately 5, as this was found to be optimal for cadmium adsorption. The mixtures were agitated at a constant speed of 120 rpm using a mechanical shaker for a contact time of 2 hours to ensure equilibrium was reached.

After adsorption, the mixtures were filtered, and the residual concentration of Cd(II) in the filtrate was determined.

Determination of Residual Metal Concentration

The concentration of cadmium ions before and after adsorption was analyzed using Atomic Absorption Spectroscopy (AAS). This technique provided accurate and reliable quantification of metal ion concentrations in solution.

The percentage removal of Cd(II) was calculated using the following expression:

$$\% \text{ Removal} = \frac{C_o - C_e}{C_o} \times 100$$

where:

C_o = initial concentration of Cd(II) (mg/L)

C_e = equilibrium concentration of Cd(II) (mg/L)

The adsorption capacity at equilibrium, q_e (mg/g), was calculated as:

$$q_e = \frac{(C_o - C_e) \times V}{m}$$

where:

C_o = initial concentration (mg/L)

C_e = equilibrium concentration (mg/L)

V = volume of solution (L)

m = mass of adsorbent (g)

Adsorption Isotherm Models

To evaluate the adsorption behavior, equilibrium data were analyzed using Langmuir and Freundlich isotherm models.

Langmuir Isotherm

The Langmuir model assumes monolayer adsorption on a homogeneous surface and is expressed as:

$$\frac{C_e}{q_e} = \frac{1}{q_{max}} C_e + \frac{1}{q_{max} K_L}$$

where:

q_e = adsorption capacity at equilibrium (mg/g)

q_{max} = maximum adsorption capacity (mg/g)

K_L = Langmuir constant (L/mg)

C_e = equilibrium concentration (mg/L)

The separation factor R_L is given by:

$$R_L = \frac{1}{1 + K_L C_o}$$

Indicating the favorability of adsorption.

Freundlich Isotherm

The Freundlich model describes adsorption on heterogeneous surfaces and is expressed as:

$$\log q_e = \frac{1}{n} \log C_e + \log K_F$$

where:

K_F = adsorption capacity constant

n = adsorption intensity

If the value of $n > 1$, it indicates favorable adsorption.

Adsorption Kinetics

To investigate the adsorption mechanism, kinetic models were applied.

Pseudo-First-Order Model

$$\log (q_e - q_t) = -\frac{k_1}{2.303} t + \log q_e$$

Where:
q_t = amount of metal ion adsorbed at time t (mg/g)
q_e = amount adsorbed at equilibrium (mg/g)
k_1 = pseudo-first-order rate constant (min^{-1})
t = contact time (min)

Pseudo-Second-Order Model

$$\frac{t}{q_t} = \frac{1}{q_e} t + \frac{1}{k_2 q_e^2}$$

where:
k_2 = pseudo-second-order rate constant (g/mg·min)

This model assumes chemisorption as the rate-limiting step.

Effect of Operational Parameters

The influence of key parameters on adsorption efficiency was investigated as follows:

1. **Initial Metal Ion Concentration:** Varied between 10–50 mg/L to study its effect on adsorption capacity.
2. **Adsorbent Dosage:** Varied from 0.1–0.5 g to determine the optimal dosage for maximum removal efficiency.

All experiments were conducted under controlled conditions, and results were analyzed to determine the adsorption performance of the prepared activated carbon.

Model Evaluation

The correlation coefficient (R^2) was used to evaluate the goodness of fit of the pseudo-first-order and pseudo-second-order kinetic models. The model with the higher R^2 value was considered to provide a more accurate representation of the adsorption kinetics of Cd(II) ions onto the prepared activated carbon, consistent with approaches reported in similar studies (Zhang et al., 2020; Zakaria et al., 2023).

RESULTS AND DISCUSSION

Characterization of Activated Carbon

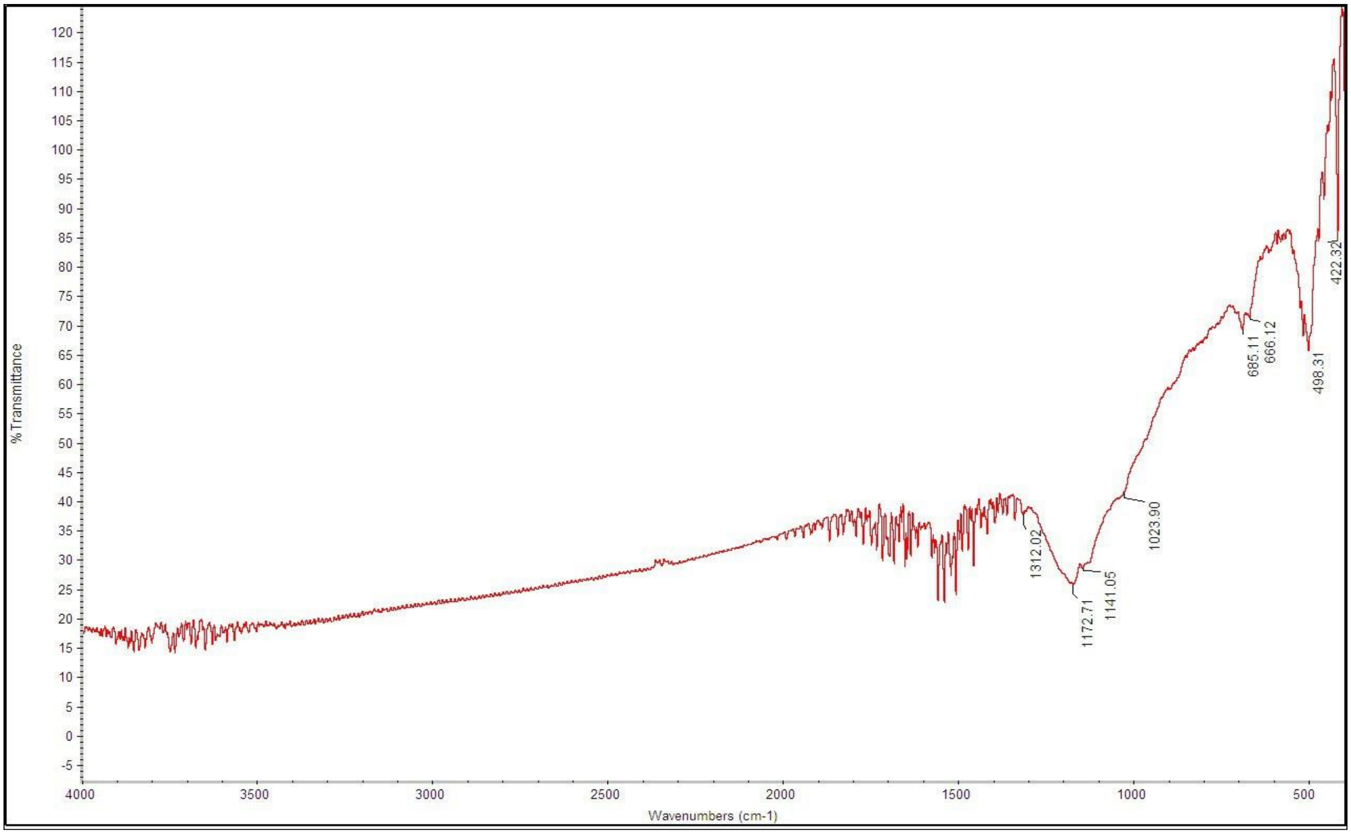

Figure 3: FTIR of Carbonized Sample

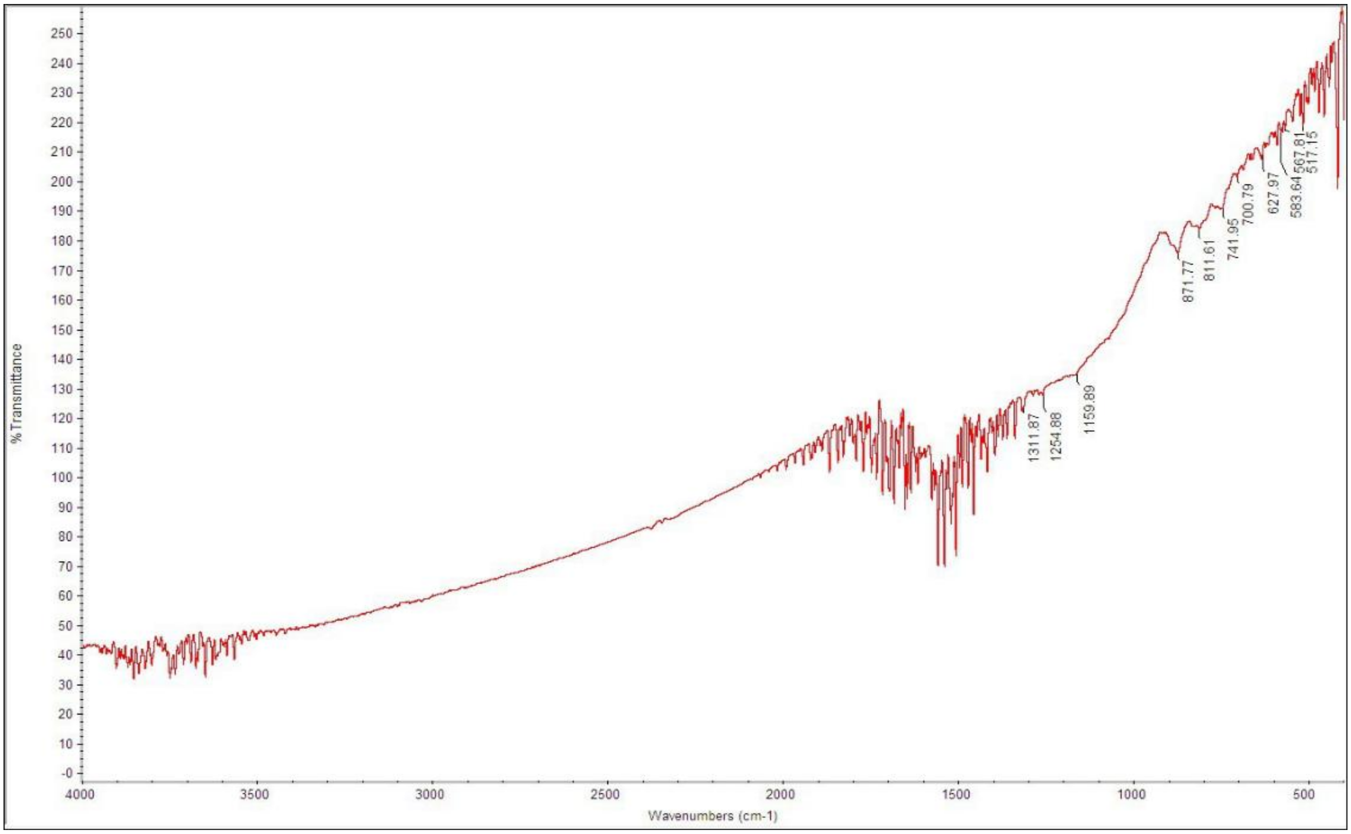

Figure 4: FTIR of Activated Carbon

Fourier Transform Infrared Spectroscopy (FTIR) analysis was conducted to identify the surface functional groups present on the prepared activated carbon. The FTIR spectrum of the carbonized and activated samples revealed the presence of key functional groups responsible for metal ion adsorption. Broad absorption bands observed around 3200–3600 cm^{-1} were attributed to hydroxyl (–OH) stretching vibrations, indicating the presence of alcohol and phenolic groups. Peaks observed near 1700 cm^{-1} correspond to carbonyl (C=O) groups, while those around 1000–1200 cm^{-1} are associated with C–O stretching vibrations.

The presence of these oxygen-containing functional groups confirms that the activated carbon surface possesses active binding sites capable of interacting with Cd(II) ions through mechanisms such as complexation and ion exchange. Chemical activation enhanced the intensity and availability of these functional groups, thereby improving the adsorption potential of the material.

AAS Analysis

The atomic absorption spectroscopy (AAS) results for cadmium (Cd^{2+}) concentrations after treatment with activated carbon under varying conditions are presented in Table 1 and 2.

Two experimental sets were studied:

Set A1- A5 : Cd^{2+} concentrations varied from 10 to 50 ppm with constant 0.5 g adsorbent.

Set B1- B5 : Adsorbent dosages varied from 0.1 to 0.5 g at a fixed Cd^{2+} concentration of 50 ppm.

All experiments were conducted at constant pH 5.

$$\% \text{ Removal} = \frac{C_i - C_f}{C_i} \times 100$$

Table 1: AAS Analysis Result of % Cadmium Removal Vs Initial Concentration

	Initial Cd (ppm)	Final Cd (ppm)	% Removal
A1	10	1.900	81.00%
A2	20	7.500	62.50%
A3	30	13.500	55.00%
A4	40	20.500	48.80%
A5	50	27.500	45.00%

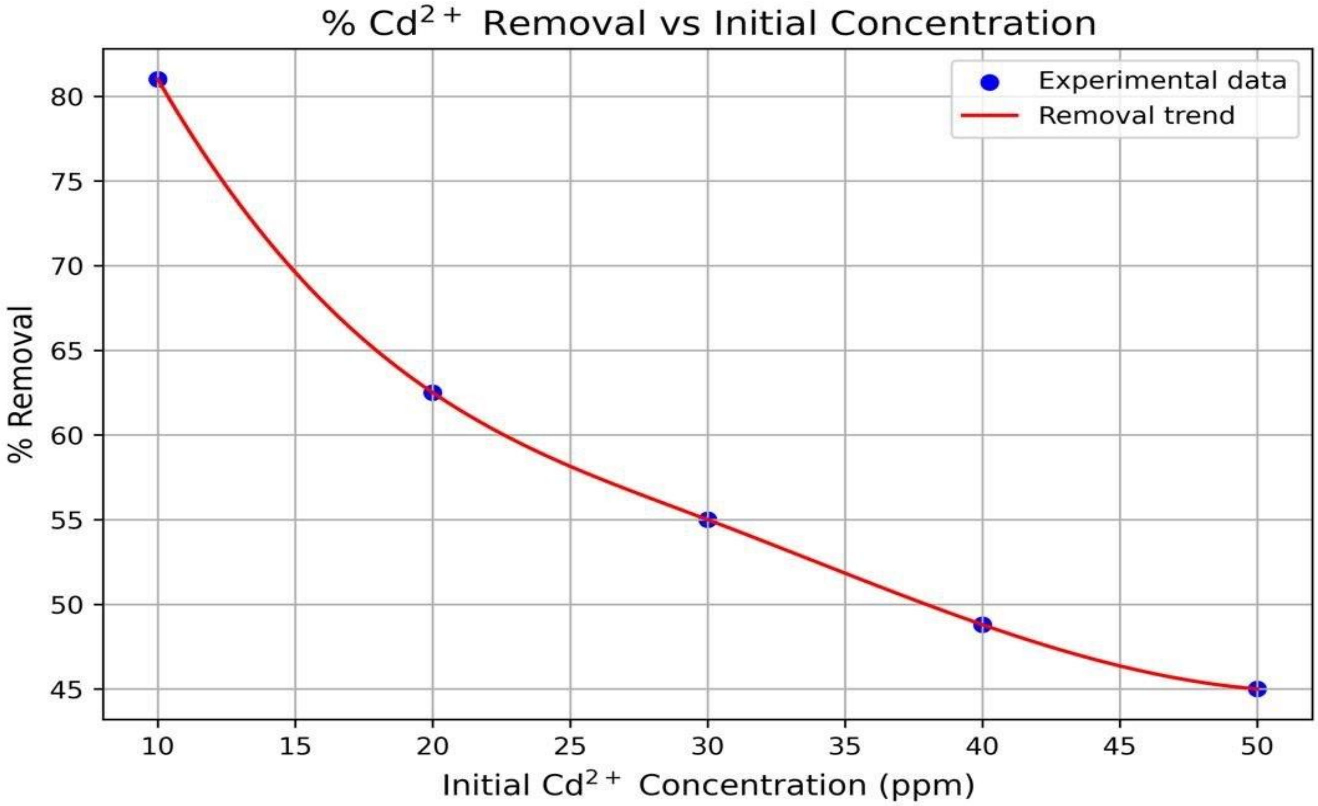

Figure 5: Graph of % Cd Removal Vs Initial Concentration

As shown in Table 1 and the Figure 5, Cd^{2+} removal decreased with increasing initial concentration, from 81.00 % at 10 ppm to 45.00 % at 50 ppm. This is due to the limited number of active sites on the activated mango seed coat surface. At lower concentrations, the ratio of available functional groups—hydroxyl (–OH) and carbonyl (C=O), as identified by FTIR—to metal ions is high, enabling efficient capture.

At higher concentrations, these groups become increasingly occupied, leading to surface saturation. This behavior aligns with the Freundlich isotherm (R^2 = 0.9834), confirming adsorption on an energetically heterogeneous surface. FTIR spectra support this, showing that Cd^{2+} ions interact with multiple binding sites of varying energy rather than a uniform monolayer.

Table 2: % Cadmium Removal Vs Adsorbent Dosage

Sample	Adsorbent Dosage	Final Cd (ppm)	% Removal

B1	0.1	9.304	81.39%
B2	0.2	9.447	81.11%
B3	0.3	9.526	80.95%
B4	0.4	9.070	81.86%
B5	0.5	9.489	81.02%

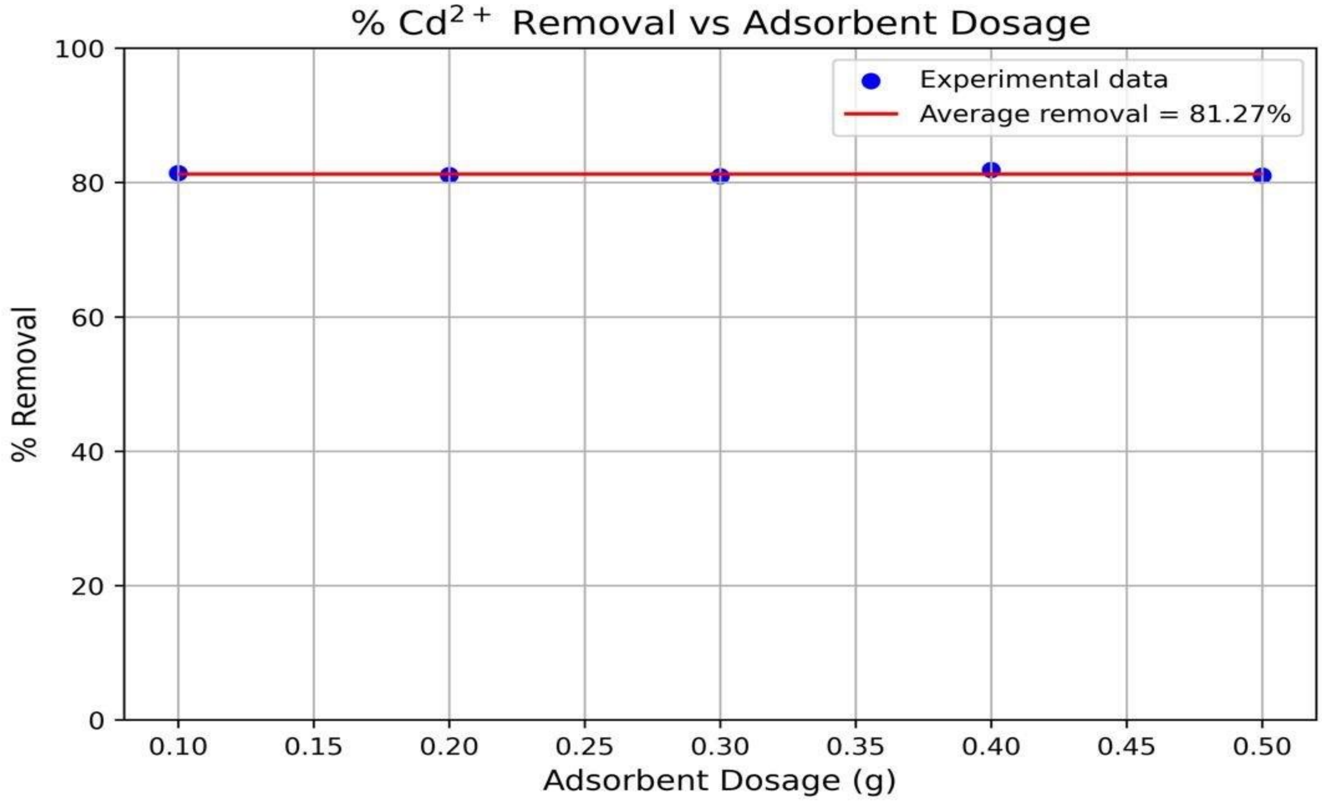

Figure 6: Graph of % Cd Removal Vs Adsorbent Dosage

The data in Table 2 and Figure 6 indicate that increasing the adsorbent dosage from 0.1 g to 0.5 g did not significantly alter the Cd^{2+} removal efficiency, which remained stable at approximately 81 %. This suggests that at the initial concentration of 50 ppm, a dosage of 0.1 g already provides an abundance of the hydroxyl (–OH) and carbonyl (C=O) functional groups identified via FTIR to satisfy the available metal ions.

The lack of further removal at higher dosages implies that the system reached an equilibrium limit where the metal ion concentration, rather than the number of active sites, became the limiting factor. Consequently, 0.1 g is identified as the optimum dosage for high-efficiency removal, demonstrating the high affinity and economic viability of the activated mango seed coat for cadmium remediation.

Adsorption Isotherm

At constant mass of 0.5 g of absorbent and volume of 0.1 L, the absorption capacity at equilibrium was evaluated below.

Table 3: Absorption Capacity at Equilibrium

Initial Conc C_o (mg/L)	**Final Conc C_e (mg/L)**	**$q_e = \frac{(C_o - C_e) \times V}{m}$ (mg/g)**
10	1.90	1.620

20	7.50	2.500
30	13.50	3.300
40	20.50	3.900
50	27.50	4.500

Langmuir Isotherm Model

Table 4: Langmuir Isotherm Results

C_e (mg/L)	q_e (mg/g)	C_e/q_e (L/g)
1.900	1.620	1.173
7.500	2.500	3.000
13.500	3.300	4.091
20.500	3.900	5.256
27.500	4.500	6.111

$$\frac{C_e}{q_e} = \frac{1}{q_{max}} C_e + \frac{1}{q_{max} K_L}$$

Plot of $\frac{C_e}{q_e}$ Vs $\mathbf{C_e}$
Slope: $\frac{1}{q_{max}}$
Intercept: $\frac{1}{q_{max} K_L}$

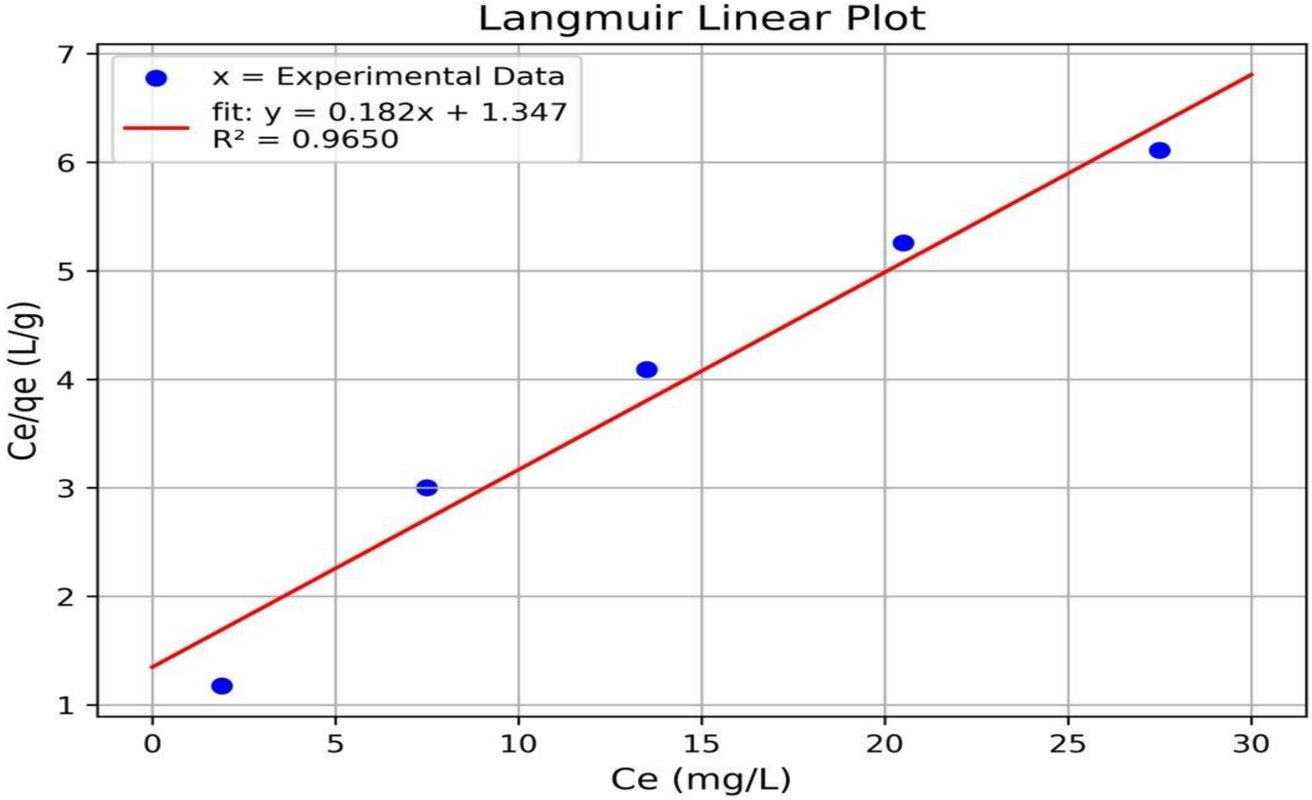

Figure 7: Langmuir Linear Plot

The Langmuir linear plot of $\frac{C_e}{q_e}$ versus C_e yielded a strong correlation coefficient ($R^2 = 0.9650$), indicating that the adsorption of Cd^{2+} follows a predictable monolayer pattern on the activated mango seed coat. From the regression equation $y = 0.182x + 1.347$, the calculated maximum monolayer capacity (q_{max}) is 5.49 mg/g and the Langmuir affinity constant (K_L) is 0.135 L/mg.

These positive constants confirm that the adsorbent possesses a finite number of specific, high-affinity binding sites, likely the hydroxyl and carbonyl groups identified in the FTIR spectra. Furthermore, the dimensionless separation factor (R_L) values for the studied concentration range (10–50 ppm) were found to be between 0.12 and 0.42. Since these values fall within the range of $0 < R_L < 1$, the adsorption process is mathematically confirmed to be highly favorable. While the surface exhibits heterogeneity, the Langmuir model successfully characterizes the saturation limit of the material.

Freundlich Isotherm Model

Table 5: Freundlich Isotherm Result

C_e (mg/L)	q_e (mg/g)	log C_e	log q_e
1.900	1.620	0.279	0.210
7.500	2.500	0.875	0.398
13.500	3.300	1.130	0.519
20.500	3.900	1.312	0.591
27.500	4.500	1.439	0.653

$$\log q_e = \frac{1}{n} \log C_e + \log K_F$$

Plot of **log q_e** Vs **log C_e**

Slope: $\frac{1}{n}$

Intercept: **log K_F**

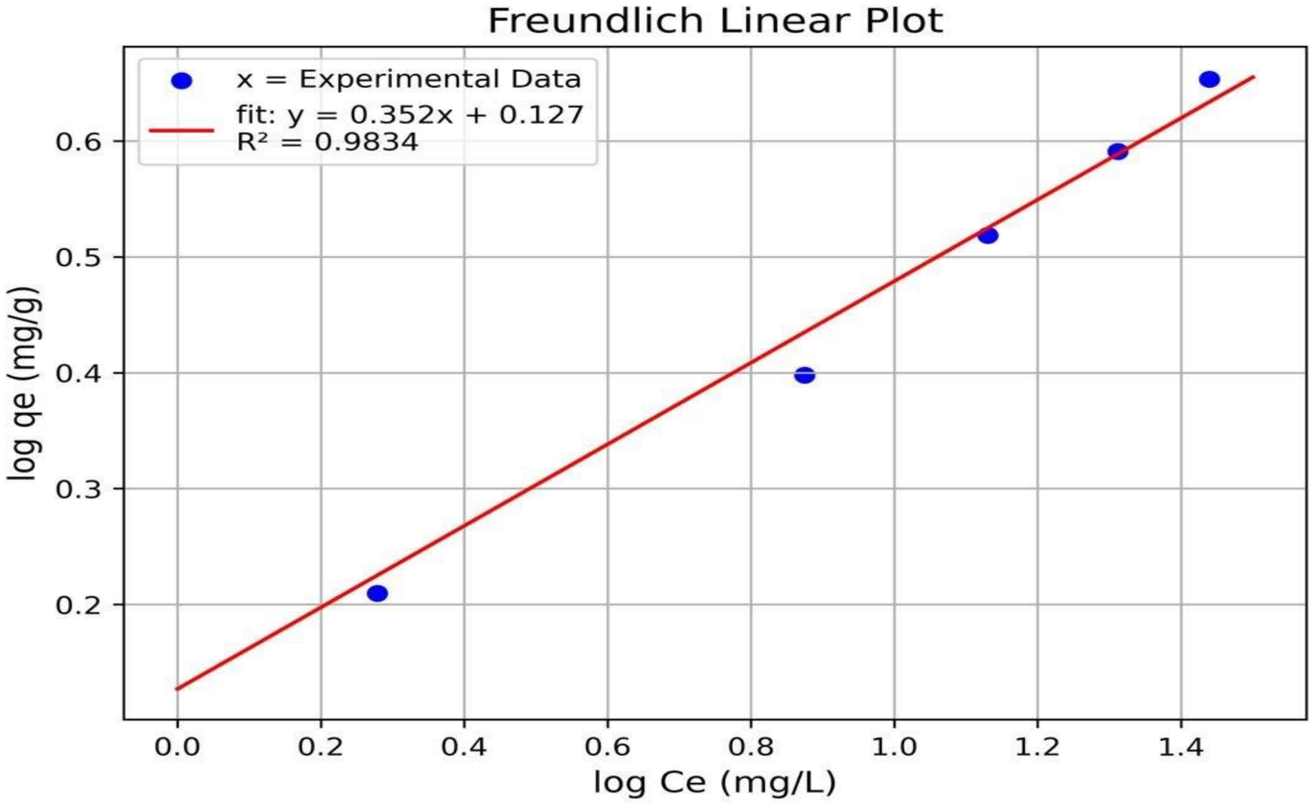

Figure 8: Freundlich Linear Plot

The Freundlich linear plot of log q_e versus log C_e yielded a strong correlation coefficient of $R^2 = 0.9834$, confirming that the adsorption of Cd^{2+} occurs on an energetically heterogeneous surface. From the regression equation y = 0.352x + 0.127, the calculated adsorption intensity ($\frac{1}{n}$) is 0.352.

Since $\frac{1}{n}$ is between 0 and 1, the process is mathematically confirmed to be highly favorable, with a calculated n value of 2.84. The intercept corresponds to a Freundlich capacity constant (K_F) of 1.34 mg/g.

These results are in excellent agreement with the FTIR analysis, as the multiple functional groups (hydroxyl and carbonyl) provide a variety of binding sites with different energy levels. This validates the multilayer adsorption behavior typical of biomass-derived activated carbon.

Adsorption Kinetics

Understanding the kinetics of adsorption is crucial for designing treatment systems and optimizing contact time. Kinetic studies help to elucidate the rate-controlling mechanisms of the adsorption process whether they are governed by chemical reaction, surface diffusion, or pore diffusion (Abd-Talib *et al.,* 2020). In this study, the experimental data were fitted to two widely used kinetic models: the pseudo first order and pseudo second order models.

The results indicated that the pseudo-second-order model provided a superior fit, suggesting that chemisorption is the dominant mechanism. This implies that Cd^{2+} ions interact with the activated mango seed coat through chemical bonding, likely involving electron sharing or exchange with the hydroxyl and carbonyl functional groups identified via FTIR.

Table 6: Adsorption Kinetics Data

Time (t,min)	q_t (mg/g)
5	2.650
10	3.240
30	3.980
60	4.310
120	4.500

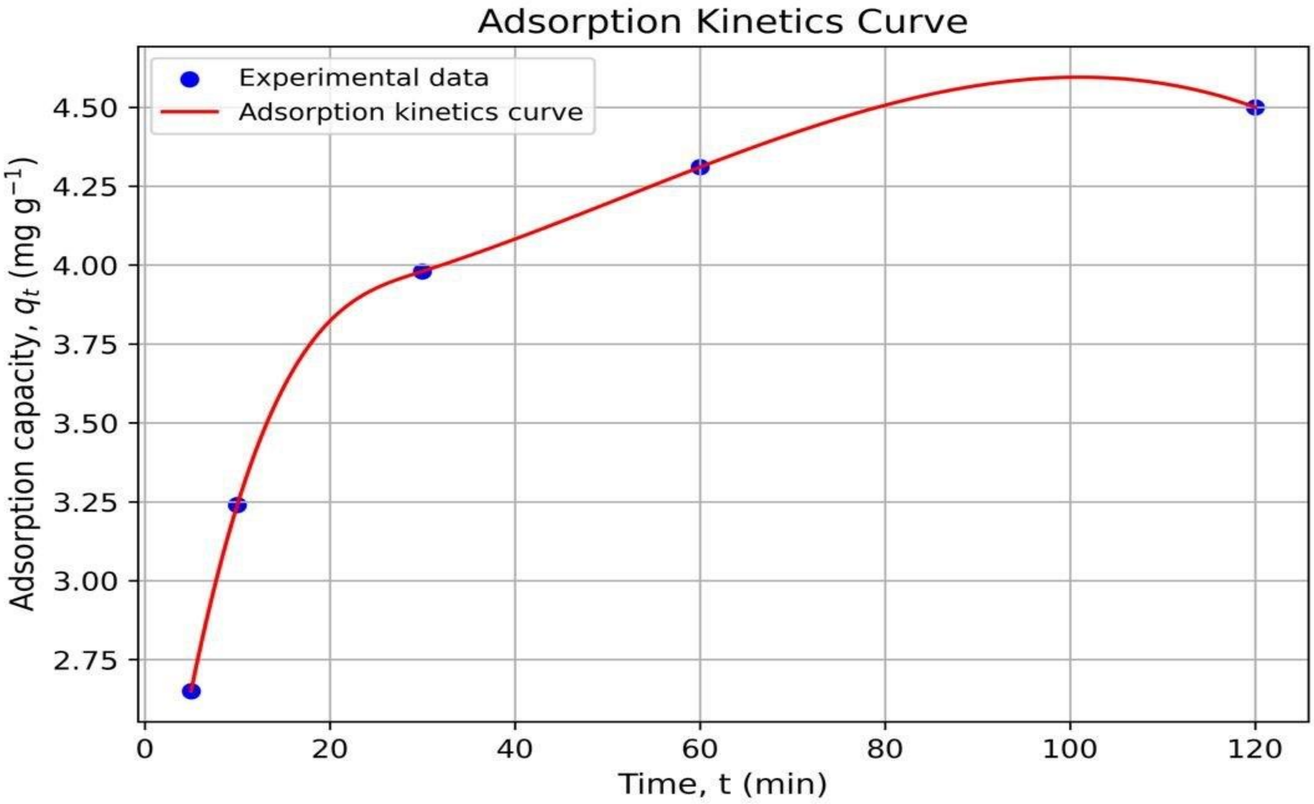

Figure 9: Adsorption Kinetics Curve

The kinetic plot of adsorption capacity (q_t) as a function of contact time (t) is presented above, illustrating the uptake behavior of Cd^{2+} ions onto mango seed-derived activated carbon. The curve shows a rapid increase in adsorption capacity at the initial stages, followed by a gradual approach to a constant equilibrium value (q_e) of 4.500 mg/g.

At the initial stage (0–10 minutes), a steep rise in q_t is observed, indicating a rapid adsorption rate. This can be attributed to the abundance of available active sites on the adsorbent surface, particularly hydroxyl and carbonyl functional groups, as well as a high concentration gradient that drives Cd^{2+} ions toward the surface.

As the contact time increases (10–60 minutes), the rate of adsorption begins to decline. This transition phase is associated with the progressive occupation of active sites and the onset of diffusion limitations, as Cd^{2+} ions penetrate into the internal pore structure of the activated carbon.

At longer contact times (around 120 minutes), the curve reaches a plateau, indicating that equilibrium has been attained. At this stage, the adsorption capacity stabilizes at 4.500 mg/g, suggesting that the available adsorption sites are saturated and no significant further uptake occurs. This plateau represents the maximum adsorption capacity under the given experimental conditions (initial concentration of 50 mg/L and adsorbent dosage of 0.5 g).

Overall, the kinetic profile demonstrates a typical adsorption behavior characterized by an initial rapid uptake followed by a slower approach to equilibrium, confirming the efficiency of the adsorbent in removing Cd^{2+} ions from solution.

Pseudo-First-Order Model

Table 7: Pseudo First Order (m = 0.5 g, q_e = 4.500 mg/g)

Time (t,min)	q_t (mg/g)	$(q_e - q_t)$	$\log(q_e - q_t)$
5	2.650	1.850	0.267
10	3.240	1.260	0.100
30	3.980	0.520	-0.284
60	4.310	0.190	-0.271
120	4.500	0.000	undefined

A plot of $\log(q_e - q_t)$ versus t allows the determination of k_1 and q_e. However, studies have shown that this model often underestimates q_e and fits best only during the early stages of adsorption (Zhang *et al.,* 2020).

The pseudo first order model, proposed by Lagergren, assumes that the rate of occupancy of adsorption sites is proportional to the number of unoccupied sites. Its linear form is given by:

$$\log (q_e - q_t) = -\frac{k_1}{2.303} t + \log q_e$$

Slope: $-\frac{k_1}{2.303}$

Intercept: $\log q_e$

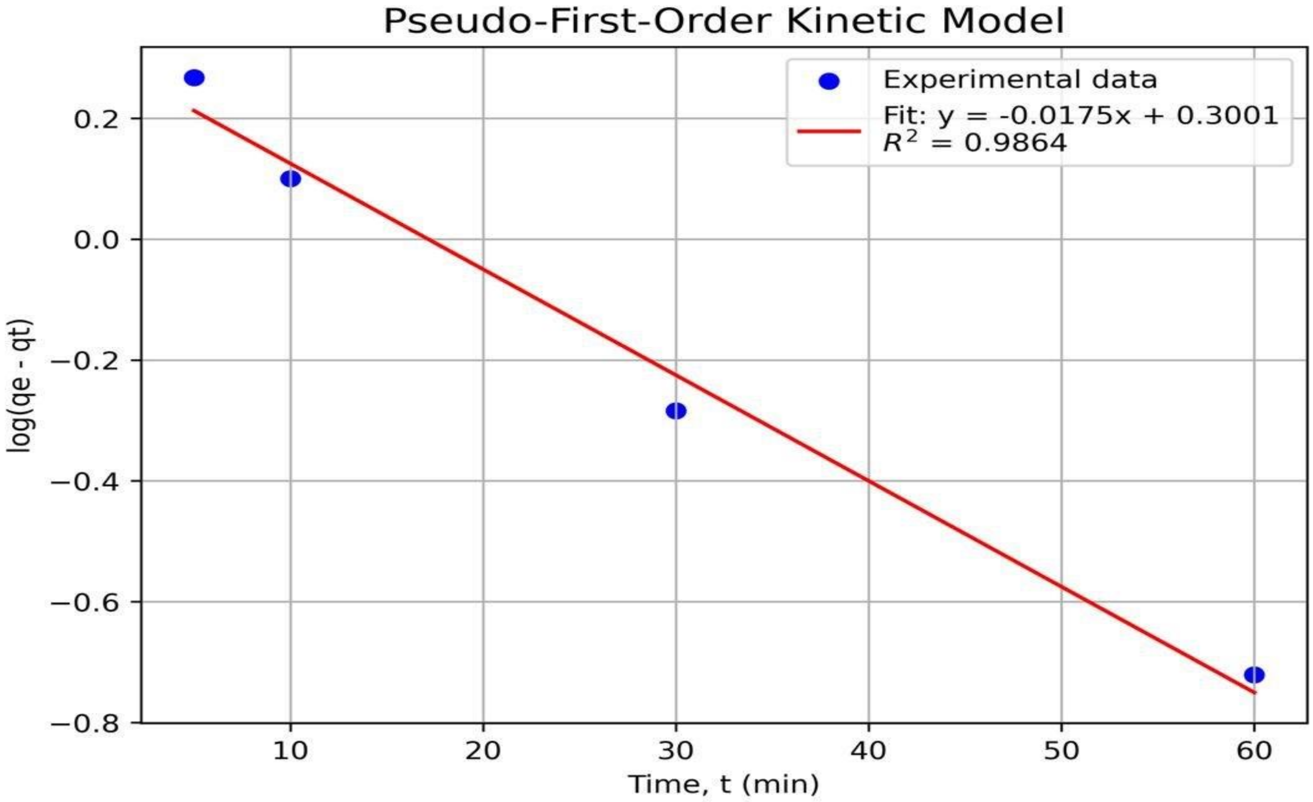

Figure 10: Plot of Pseudo First Order Kinetic Model

The Pseudo First Order linear plot of log($q_e - q_t$) versus time (t) yielded a correlation coefficient ($R^2 = 0.9864$), providing an initial mathematical framework for the adsorption kinetics of Cd^{2+} on the activated mango seed coat. From the regression equation $y = -0.0175x + 0.3001$, the calculated adsorption rate constant (k_1) is found to be 0.0403 min^{-1}, and the theoretical equilibrium adsorption capacity (q_e, calc) is 1.996 mg/g.

While the correlation coefficient indicates a relatively strong linear relationship, a significant discrepancy exists between the experimental equilibrium capacity (q_e, exp = 4.500 mg/g) and the calculated value (q_e, calc = 1.996 mg/g). This large deviation suggests that the Pseudo First Order model, which typically characterizes a process controlled by physical diffusion or physisorption, does not fully describe the rate-limiting step of this system.

Instead, the kinetic behavior points toward a more complex interaction. The failure of this model to accurately predict the saturation limit (q_e) confirms that the removal of cadmium is not merely a surface-layer physical trapping. Rather, it is likely governed by chemisorption, where the rate is determined by chemical bonding and ion exchange with the high-affinity functional groups specifically the hydroxyl and carbonyl groups previously identified. Consequently, the Pseudo Second Order model is required to more accurately characterize the definitive chemical nature of the Cd^{2+} uptake.

Pseudo-Second-Order Model

Table 8: Pseudo Second Order (q_e = 4.500mg/g)

Time (t,min)	q_t (mg/g)	$y = t/q_t$ (min.g/mg)
5	2.650	1.8868
10	3.240	3.0864
30	3.980	7.5377
60	4.310	13.9211

120	4.500	26.6667

This model typically gives a better fit for systems involving chemical bonding, especially in biosorbents functionalized with oxygen-containing groups (Abd-Talib *et al.,* 2020; Zakaria *et al.,* 2023). A plot of t/q_t versus t yields a straight line, from which q_e and k_2 can be determined.

The pseudo-second-order model assumes that chemisorption is the rate-limiting step, involving valence forces through electron sharing or exchange between adsorbent and adsorbate (Abubakar et al., 2025). The linear form of the equation is:

$$\frac{t}{q_t} = \frac{1}{q_e}t + \frac{1}{k_2 q_e^2}$$

Slope: $\frac{1}{q_e}$

Intercept: $\frac{1}{k_2 q_e^2}$

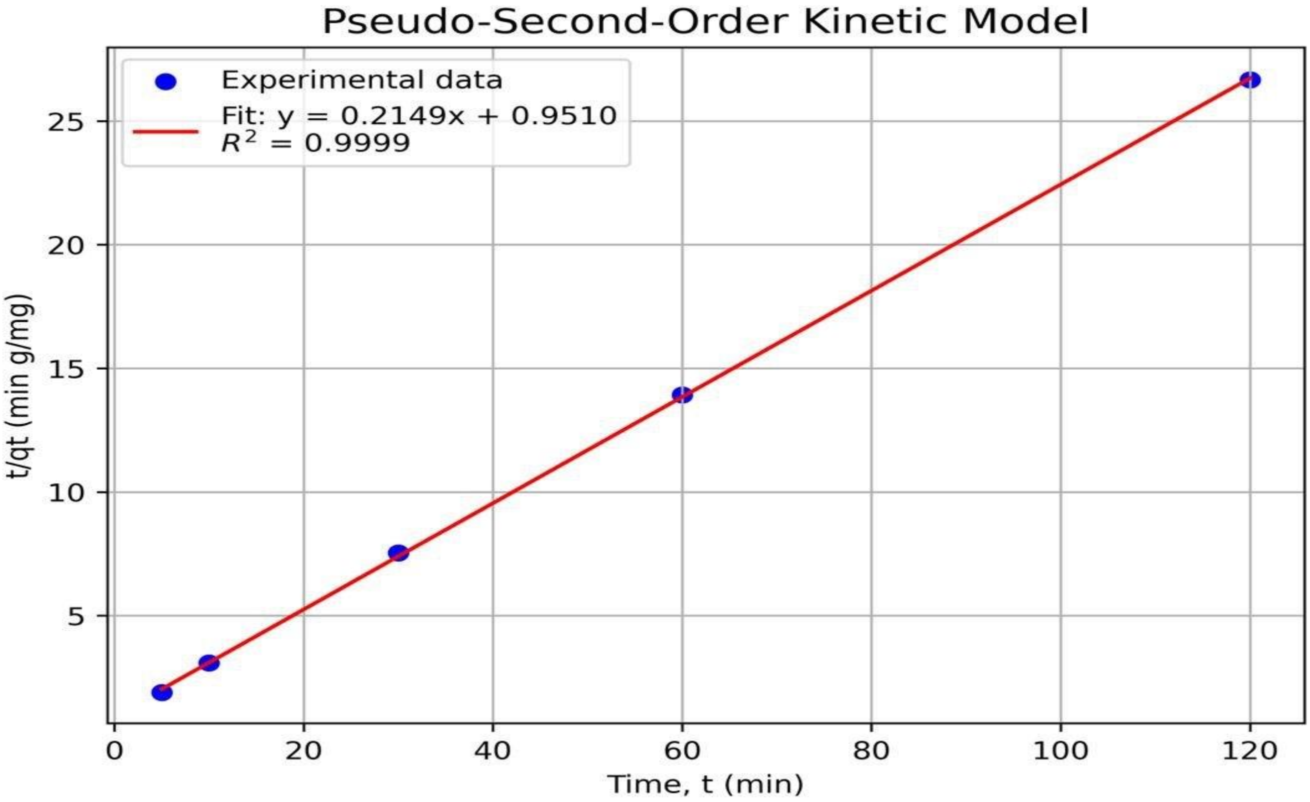

Figure 11: Plot of Pseudo Second Order Kinetic Model

The Pseudo Second Order linear plot of t/q_t versus time (t) yielded an exceptionally high correlation coefficient (R^2 = 0.9999), indicating that the adsorption of Cd^{2+} perfectly fits this kinetic model. From the regression equation y = 0.2149x + 0.9510, the calculated equilibrium adsorption capacity (q_e, calc) is 4.654 mg/g, which shows excellent agreement with the experimental value (q_e, exp = 4.500 mg/g). Additionally, the calculated second-order rate constant (k_2) is 0.0485 g/mg·min.

This near-perfect alignment between the theoretical and experimental data points confirms that the rate-limiting step in the removal of cadmium is not physical diffusion, but rather chemisorption. The high R^2 value and the accurate prediction of the saturation limit indicate that the process involves the sharing or exchange of electrons between the Cd^{2+} ions and the adsorbent surface.

Specifically, this chemical interaction is facilitated by the specific, high-affinity binding sites primarily the hydroxyl and carbonyl groups previously identified. Because the adsorption rate depends on the capacity of the adsorbent and not just the concentration of the solution, the Pseudo Second Order model successfully characterizes the definitive chemical uptake and the stability of the metal–carbon complex on the activated mango seed coat.

Adsorption Efficiency

Effect of Initial Cd(II) Concentration

The observed decrease in Cd^{2+} removal from 81.00 % to 45.00 % as initial concentration increased (10–50 ppm) is a classic characteristic of adsorbent saturation. At the lower concentration of 10 ppm, the ratio of available surface area to the total number of metal ions in the solution is at its highest. This provides the Cd^{2+} ions with maximum access to the hydroxyl (–OH) and carbonyl (C=O) functional groups identified in the FTIR analysis.

As the concentration increases to 50 ppm, the absolute amount of cadmium adsorbed per unit mass (q_e) actually increases due to the higher concentration gradient, which acts as a powerful driving force for mass transfer. However, because the adsorbent dosage was kept constant at 0.5 g, the total number of active binding sites is fixed. Once these high-energy sites are occupied, the percentage of the total ions removed naturally drops.

This behavior confirms that the adsorption process is "site-limited." The fact that the removal does not drop to zero even at 50 ppm supports the Freundlich model findings ($R^2 = 0.9834$), suggesting that the activated mango seed coat possesses an energetically heterogeneous surface. This means that after the most reactive sites are filled, secondary sites with different energy levels continue to contribute to the 45 % removal observed at higher concentrations.

In conclusion, the activated mango seed coat is most efficient in dilute conditions, achieving an optimal 81.00% removal. While higher concentrations increase the loading capacity (q_e) via an enhanced driving force, the declining removal percentage at 50 ppm confirms the eventual saturation of the surface functional groups. This highlights the material's high affinity for cadmium and its suitability for treating metal-contaminated wastewater within the studied concentration range.

Effect of Adsorbent Dosage

The investigation into adsorbent dosage (0.1 g to 0.5 g) revealed that Cd^{2+} removal remained nearly constant at approximately 81 % after the initial 0.1 g, identifying it as the optimal dosage for balancing efficiency and material usage. This plateau is attributed to the aggregation of adsorbent particles at higher masses, which causes the overlapping of hydroxyl and carbonyl active sites and reduces the effective surface area available for metal interaction.

In conclusion, while increasing the mass provides more total sites, the marginal improvement beyond 0.1 g confirms that the system reached an equilibrium limit, making the lower dosage the most economically viable choice for cadmium remediation using activated mango seed coat.

Adsorption Isotherm Analysis

The equilibrium adsorption of Cd^{2+} onto activated mango seed coat was evaluated using both the Langmuir and Freundlich models to determine the nature of the surface interactions. The experimental data demonstrated a superior mathematical fit to the Freundlich model ($R^2 = 0.9834$), indicating that the adsorption process occurs on an energetically heterogeneous surface rather than a uniform one. This is physically supported by the FTIR results, which identified multiple functional groups—including hydroxyl (–OH) and carbonyl (C=O)—that provide a range of binding sites with varying affinities. The calculated value of $n = 2.84$ ($1 < n < 10$) confirms that the process is highly favorable under the studied conditions.

While the Langmuir model was statistically secondary ($R^2 = 0.9650$), it successfully estimated a maximum monolayer adsorption capacity (q_{max}) of 5.34 mg/g, representing the theoretical saturation point. The calculated separation factor (R_L) values remained between 0 and 1, further validating the favorability of the adsorption. In conclusion, while the Langmuir model provides a useful saturation limit, the superior fit of the Freundlich model more accurately describes the real-world chemistry of the activated mango seed coat, where diverse functional groups interact with Cd^{2+} ions across multiple energy levels in a multilayer arrangement.

Adsorption Mechanism

The adsorption of Cd(II) onto mango seed-derived activated carbon is governed by multiple mechanisms, including:

1. Electrostatic attraction between Cd(II) ions and negatively charged adsorbent surfaces
2. Ion exchange involving replacement of surface ions with Cd(II)
3. Surface complexation with functional groups such as –OH and –COOH
4. Pore diffusion into the internal structure of the adsorbent

Reusability of the Adsorbent

The reusability of the activated carbon was evaluated through adsorption–desorption cycles. The results showed that the adsorbent retained a significant portion of its adsorption capacity after reuse, although a gradual decline in efficiency was observed.

This decrease may be due to incomplete desorption of Cd(II) ions or slight structural degradation of the adsorbent during regeneration. Nevertheless, the ability to reuse the adsorbent demonstrates its potential for cost-effective and sustainable application in water treatment.

Comparison with Other Adsorbents

The adsorption performance of mango seed-derived activated carbon compares favorably with other low-cost adsorbents reported in the literature. Its relatively high removal efficiency, combined with its low cost and abundance, makes it a competitive alternative to commercial activated carbon.

The results further highlight the potential of agricultural waste materials as effective adsorbents for heavy metal removal, contributing to both environmental remediation and waste management.

Summary of Findings

Results of this study demonstrate that:

- Mango seed coat-derived activated carbon possesses functional groups suitable for Cd(II) adsorption
- Adsorption efficiency decrease with increase in initial metal concentration
- Optimal adsorbent dosage was observed at 0.1 g
- The Freundlich isotherm best describes the adsorption process
- Adsorption follows pseudo-second-order kinetics, indicating chemisorption
- The adsorbent shows good potential for reuse

Overall, these findings confirm that activated mango seed coat is a highly effective, low-cost, and sustainable alternative to commercial adsorbents for Cd^{2+} removal, offering a promising solution for both environmental remediation and agricultural waste management.

CONCLUSION

This study successfully demonstrated the potential of activated carbon derived from mango (Mangifera indica) seed coats as an efficient and low cost adsorbent for the removal of Cd^{2+} ions from aqueous solutions. FTIR analysis confirmed that the prepared adsorbent possesses favorable physicochemical properties, specifically the presence of hydroxyl and carbonyl functional groups capable of strong heavy metal sequestration.

Batch adsorption experiments revealed that while the absolute adsorption capacity (q_e) increased with concentration due to a stronger driving force, the percentage removal decreased from 81.00 % to 45.00 % as initial Cd^{2+} concentration rose from 10 to 50 mg/L. Furthermore, an adsorbent dosage of 0.1 g was identified as optimal, providing maximum removal efficiency while maintaining economic material usage.

The equilibrium data were best described by the Freundlich isotherm model ($R^2 = 0.9834$), indicating multilayer adsorption on an energetically heterogeneous surface. Kinetic studies confirmed that the process follows pseudo second order kinetics, suggesting that chemisorption—driven by electrostatic attraction, ion exchange, and surface complexation—is the dominant mechanism.

With demonstrated reusability and high stability, this mango seed derived activated carbon represents a sustainable and economically viable alternative to conventional adsorbents. These findings highlight a promising path for environmental remediation that simultaneously addresses agricultural waste management through a circular economy approach.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

1. Further studies should investigate the adsorption performance of the adsorbent in multi-component systems to simulate real wastewater conditions.
2. Advanced characterization techniques such as SEM, BET surface area analysis, and XRD should be employed to provide deeper insight into the structural properties of the adsorbent.
3. Column adsorption studies should be conducted to evaluate the performance of the adsorbent under continuous flow conditions.

4. Regeneration and reuse studies should be optimized to enhance the long-term economic viability of the adsorbent.

5. Scale-up studies and cost-benefit analyses should be carried out to assess the feasibility of industrial application.

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