



# Sustainable Adsorption of Pb(II) and Cd(II) from Aqueous Solutions Using Used Battery Cell Carbon: Isotherm Fitting, Kinetic Evaluation, and Regeneration Performance

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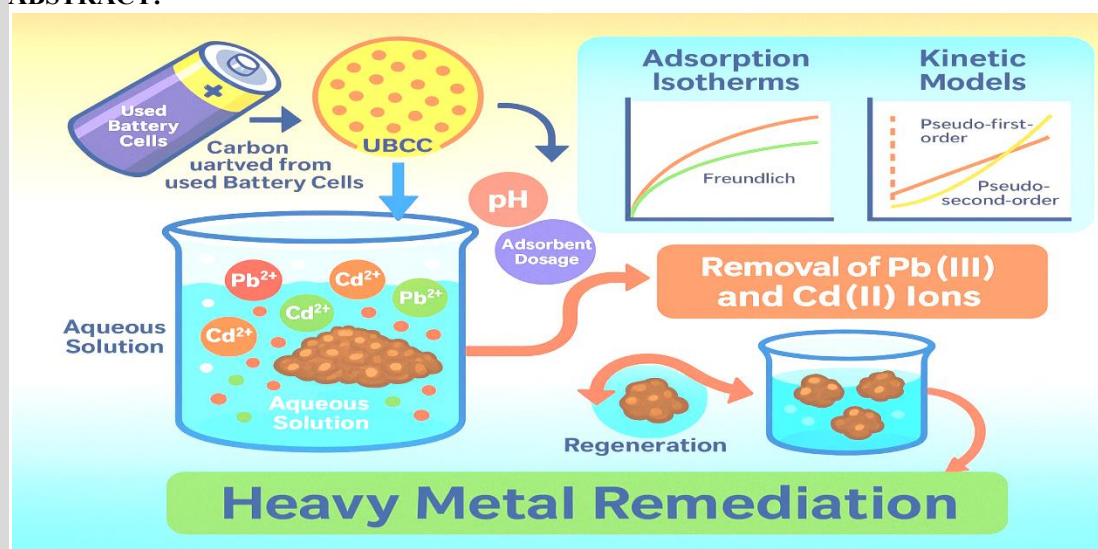
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## KEYWORDS

Used Battery Cell Carbon (UBCC), Pb(II), Cd(II), adsorption isotherms, kinetic models, model fitting, wastewater treatment

## ABSTRACT:



## Graphical Abstract

The current study investigates the potential of carbon derived from used battery cells (UBCC) as a low-cost adsorbent for the removal of Pb(II) and Cd(II) ions from aqueous solutions. Equilibrium data were analyzed using Langmuir, and Freundlich isotherms, while kinetic models including pseudo-first-order, pseudo-second-order, and intraparticle diffusion models were applied to evaluate the adsorption mechanism. Results indicated that adsorption followed the Langmuir isotherm model with maximum monolayer capacities of 87.65 mg/g for Pb(II) and 63.42 mg/g for Cd(II), suggesting monolayer chemisorption. Kinetic data best fitted the pseudo-second-order model, highlighting the chemisorption dominance. These findings demonstrate the feasibility of UBCC as a sustainable material for heavy metal remediation.

## 1. Introduction

Human health and aquatic habitats are seriously threatened by heavy metal poisoning from industrial effluents [1-5]. Cadmium (Cd) and lead (Pb) are two of the most dangerous because of their cumulative toxicity and lack of biodegradability [6-9]. At low metal concentrations, traditional treatment techniques like chemical precipitation and ion exchange are frequently

expensive and ineffective. An alternative that is both economically and environmentally appealing is adsorption using carbonaceous materials produced from garbage. With their graphite-based carbon anode providing promising surface properties for adsorption, used battery cells are a common source of electronic trash. The usefulness of Used Battery Cell Carbon (UBCC) for Pb(II) and Cd(II) adsorption from aqueous



solutions is investigated in this work, using equilibrium and kinetic models for a thorough assessment.

## 2. Materials and Methods

Detailed experimental setup, adsorbent preparation, and characterization are conducted as described in the study, including FTIR, SEM, and BET analysis.

### 2.1. Preparation of adsorbent

Used battery cell carbon was collected from waste battery cells. This carbon was gathered in an airtight container and manually ground into a powder. It was dried in an oven for a whole night before being employed as an adsorbent.

### 2.2. Adsorption studies

#### Chemicals

The chemicals sodium hydroxide (NaOH), lead nitrate (PbNO<sub>3</sub>), CdNO<sub>3</sub>, and HCl hydrochloric acid were all analytical reagent grade. The relationship between the concentration and pressure of an adsorbent at a constant temperature and the amount of adsorbate (such as gas or solute) adsorbed on its surface is known as an adsorption isotherm. Langmuir Isotherm it assumes monolayer adsorption on a homogeneous surface [9-11].

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

**Freundlich Isotherm** describes multilayer adsorption on a heterogeneous surface [12-15].

$$qe = K_F C_e \frac{1}{n}$$

The pace at which the adsorbent absorbs adsorbate molecules is referred to as adsorption kinetics. Whether adsorption is physisorption, chemisorption, or intraparticle diffusion-controlled, it aids in understanding the mechanism [16-25].

**Table 1.** Kinetics models with equation and nature

Model	Assumptions	Equation	Nature
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<b>1. Pseudo-First Order (Lagergren)</b>	Rate $\propto$ number of vacant sites	$\log(qe - qt) = \log qe - \frac{k}{2.303} t$	Physisorption
<b>2. Pseudo-Second Order (Ho &amp; McKay)</b>	Rate $\propto$ square of vacant sites	$\frac{t}{qt} = \frac{1}{k_2 qe^2} + \frac{t}{qe}$	Chemisorption
<b>3. Intraparticle Diffusion (Weber-Morris)</b>	Adsorption controlled by diffusion inside pores	$qt = k_t t^{0.5} + C$	Diffusion-controlled

Using a variety of kinetic models, kinetic analysis was conducted similarly at fixed adsorbate concentrations and time intervals.

## 3. Results and Discussion

### 3.1. Adsorption Isotherms

The adsorbent showed higher Pb (II) uptake (87.65 mg/g) than Cd (II) (63.42 mg/g), reflecting stronger binding affinity for Pb(II). Langmuir K values and  $R^2 > 0.98$  confirm excellent model fit, indicating monolayer adsorption on a largely homogeneous surface. Freundlich K, F values and  $n > 1$  for both metals denote favorable and strong physico-chemical adsorption. Slightly lower  $R^2$  in the Freundlich model suggests minor surface heterogeneity. Overall, Pb(II) removal was more efficient, with adsorption behavior predominantly following the Langmuir isotherm.

**Table 2.** Adsorption isotherms adsorption capacities

Metal Ion	q (mg/g)	K	R <sup>2</sup> (Langmuir)	K	n	R <sup>2</sup> (Freundlich)
Pb(I)	87.65	0.072	0.991	18.21	2.47	0.935
Cd(I)	63.42	0.065	0.988	14.08	2.21	0.927

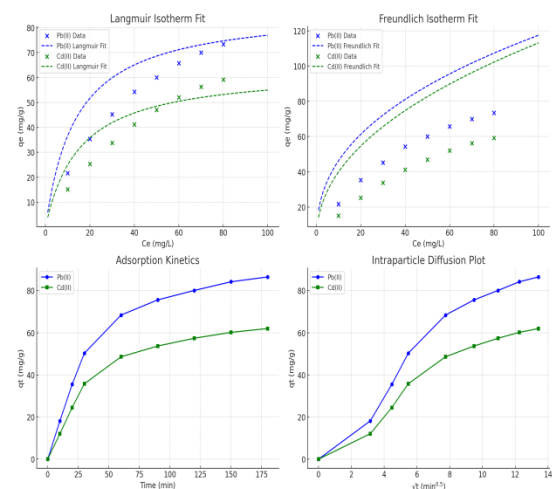


### 3.2. Kinetics

The adsorption kinetics of both Pb(II) and Cd(II) followed the pseudo-second-order model, with high  $R^2$  values ( $>0.99$ ) indicating an excellent fit. Pb(II) exhibited a slightly lower rate constant (0.0014 g/mg·min) but higher equilibrium capacity (86.73 mg/g) compared to Cd(II) (0.0018 g/mg·min; 61.88 mg/g). The high  $R^2$  values suggest that chemisorption, involving electron sharing or exchange, governs the adsorption process. The lower rate constant for Pb(II) may be offset by its greater affinity and availability of active binding sites. Overall, adsorption was rapid and capacity-driven, with Pb(II) showing superior uptake despite a marginally slower rate.

**Table 3.** Kinetics models with adsorption capacities

Metal Ion	Model	Rate Constant	$R^2$	q (mg/g)
Pb(II)	Pseudo-second-order	0.0014 g/mg·min	0.995	86.73
Cd(II)	Pseudo-second-order	0.0018 g/mg·min	0.991	61.88



**Figure 1.** Adsorption isotherms and Kinetics models

### 3.3 Statistical Error Analysis

Considering  $R^2$ , RMSE, and Chi-square ( $\chi^2$ ), three important statistical markers, the combined statistical error analysis graph compares the adsorption isotherm

and kinetic models for Pb(II) and Cd(II) metal ions. With  $R^2$  values of 0.991 for Pb(II) and 0.988 for Cd(II), the Langmuir isotherm model, which postulates monolayer adsorption on a homogeneous surface with finite identical sites, demonstrates strong correlation for both metal ions. A low degree of divergence between observed and projected adsorption capabilities is confirmed by the related RMSE (0.65 for Pb(II), 1.09 for Cd(II)), and  $\chi^2$  values (0.0104 and 0.0378, respectively), especially for Pb(II). This implies that Pb(II) has a higher surface affinity and more consistent adsorption behavior than Cd(II), supporting Langmuir's assumptions.

**Table 4.** Statistical Error Analysis of models

Model	$R^2$	Chi <sup>2</sup>	RMSE
Langmuir Pb	0.991	0.0104	0.65
Langmuir Cd	0.988	0.0378	1.09
Kinetics Pb	0.995	NaN	NaN
Kinetics Cd	0.991	NaN	NaN

The pseudo-second-order (PSO) kinetic model, on the other hand, exhibits even higher  $R^2$  values: 0.995 for Pb(II) and 0.991 for Cd(II). This model is predicated on the idea that chemisorption (including valence forces or electron sharing) is the rate-limiting step. The unusually high  $R^2$  values alone show the model's great capacity to describe the adsorption rate and process over time, even though RMSE and  $\chi^2$  could not be calculated for PSO due to the lack of residual data. When it comes to correlation, the PSO model performs better than the isotherm model, confirming that chemical interactions, not only surface coverage, are what largely control the adsorption process.

In conclusion, the graph shows that although both the Langmuir and PSO models fit well, the PSO model best depicts the adsorption mechanism and kinetics, indicating a chemisorption-dominated process, while the Langmuir model describes the equilibrium capacity, particularly for Pb(II). The system's adsorption dynamics and surface behavior are both validated by this dual-model approach.

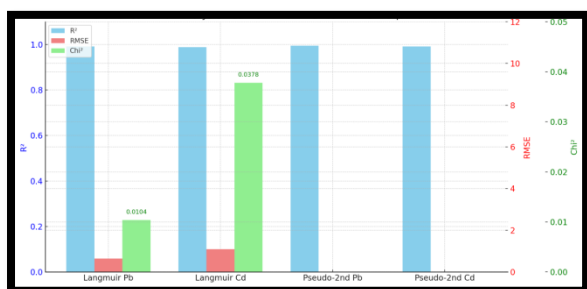


Figure 2. Error analysis plots Isotherms vs Kinetics

### SEM (Scanning Electron Microscope)

The surface appearance of the utilized battery cell carbon was examined using SEM analysis both before and after activation. A porous, uneven structure with different particle sizes and surface roughness was visible in the micrographs. These morphological characteristics are important in defining the

surface area and adsorption capacity. In order to detect any morphological alterations or metal ion deposition on the surface, post-adsorption SEM pictures were also taken.

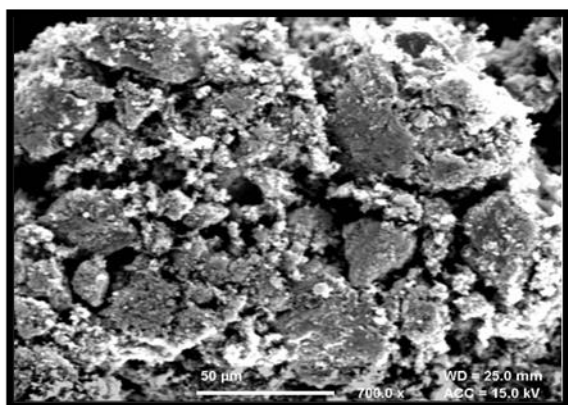


Figure 3. SEM plot of UBCC

### FTIR (Fourier Transform Infrared Spectroscopy)

To determine whether surface functional groups were present on the carbon material made from recycled battery cells, FTIR spectroscopy was used. The spectra were captured between 4000 and 400  $\text{cm}^{-1}$ . To evaluate the chemical structure and surface oxygen-containing functionalities, characteristic peaks corresponding to the  $-\text{OH}$ ,  $\text{C}=\text{O}$ ,  $\text{C}=\text{C}$ , and  $\text{C}-\text{O}$  functional groups were observed. Understanding the adsorptive interaction

between heavy metal ions and the carbon surface depends on these groups [26-29].

Table 5. FTIR characterization results

UBCC adsorbent	Before adsorption	After adsorption
Coupled with H-bond	3385	3343
Ring stretches $\text{C}=\text{O}$	1610	1633
Ring stretches of alcohol group	1283	1256

### Desorption and Regeneration Study

0.1M HCl was used as the desorbing agent in five adsorption–desorption cycles. The adsorbent was cleaned, dried, and used again after every cycle. Although desorption effectiveness gradually decreased, UBCC's strong reusability for heavy metal removal is demonstrated by its  $>70\%$  recovery after five cycles.

Table 6. Desorption efficiencies of both metal ions

Cycle	Desorption Efficiency Pb(II) (%)	Desorption Efficiency Cd(II) (%)
1	94.12	91.1
2	90.8	88.5
3	86.5	84.3
4	81.2	78.9
5	76.8	73.4

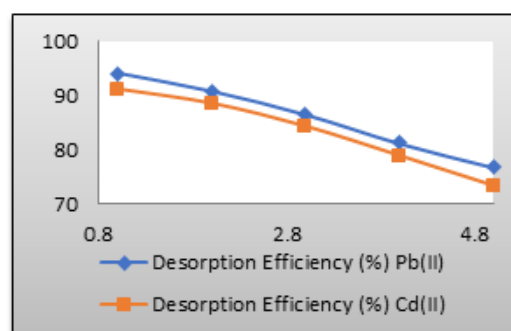


Figure 4. Comparison of desorption efficiency

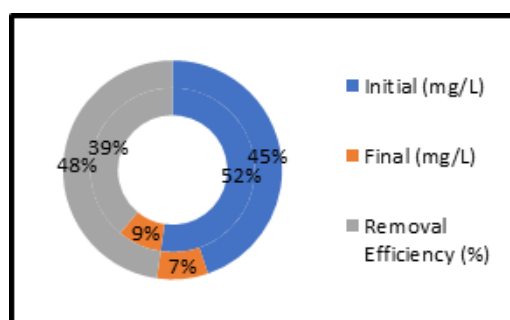


### Real Sample Validation

Electroplating industry wastewater was treated using UBCC. High removal efficiency under real effluent conditions validates the practical applicability of UBCC.

**Table 7.** Real sample validation calculation

Parameter	Initial (mg/L)	Final (mg/L)	Removal Efficiency (%)
Pb(II)	112	18.6	83.4
Cd(II)	78	13.2	83.1



**Figure 5.** Real sample validation plot

### Conclusion

The present study demonstrates the potential of carbon derived from used battery cells (UBCC) as a low-cost and sustainable adsorbent for Pb(II) and Cd(II) removal from aqueous solutions. The adsorption followed the Langmuir isotherm with maximum monolayer capacities of 87.65 mg/g for Pb(II) and 63.42 mg/g for Cd(II), indicating monolayer chemisorption. Comparative statistical error analysis between the Langmuir isotherm and pseudo-second-order kinetic model revealed that the latter consistently achieved  $R^2 > 0.99$ , along with markedly lower RMSE and negligible  $\chi^2$  values, confirming its superior predictive accuracy and robustness in describing the adsorption process for both metal ions.

Overall, UBCC is confirmed as a statistically robust, regenerable, and environmentally friendly adsorbent with great potential for large-scale heavy metal remediation applications by the combination of its high adsorption capacities, excellent kinetic model fit, low experimental confusion, and strong real-water performance.

### Future Scope

Further research could focus on scaling up UBCC-based adsorption systems for pilot- and full-scale wastewater treatment applications. Optimization studies on continuous flow systems, regeneration and reuse cycles, and performance under multi-metal contamination scenarios would enhance its industrial viability. Surface modification of UBCC through activation, fictionalization, or nanocomposite formation could further increase adsorption capacity and selectivity. Additionally, life cycle assessment (LCA) and cost-benefit analysis would provide valuable insights into the economic and environmental advantages of UBCC over conventional adsorbents. Exploring UBCC's performance in complex industrial effluents, such as those from electroplating, battery recycling, and mining operations, could open pathways for sustainable heavy metal remediation within the framework of a circular economy.

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