



<https://doi.org/10.47430/ujmr.25102.006>

Received: 1st August, 2025

Accepted: 6th December, 2025



Optimized Adsorptive Removal of Pb²⁺ and Cd²⁺ from Maize Flour Mill Wastewater Using Modified Activated Carbon

*¹Amoo Afeez Oladeji , ¹Ridwan Musa , ¹Ijanu Emmanuel Madu , ^{1,2}Adeleye Adeniyi Olarewaju , and ²Amoo Florence Kemi 

¹Department of Environmental Sciences, Faculty of Physical Sciences, Federal University Dutse, Jigawa State, Nigeria

²Department of Microbiology & Biotechnology, Faculty of Life Sciences, Federal University Dutse, Jigawa State, Nigeria

*Corresponding author: afeezoladeji@fud.edu.ng; +234-80-6231-5520

Abstract

Heavy metal contamination in wastewater poses a serious environmental and public health concern globally, particularly in developed regions, where cost-effective remediation methods are needed. This study investigates the optimized removal of Pb²⁺ and Cd²⁺ from maize flour mill wastewater using modified wood-based biomass biochar (WBBC). The activated carbon was prepared chemically via phosphoric acid activation to enhance its adsorption capacity, while batch adsorption tests were conducted to examine the effects of contact time, pH, and adsorbent dosage on its efficacy for metal removal. The physicochemical characteristics of the studied wastewater sample indicated elevated pollution levels, necessitating pretreatment prior to environmental discharge. The produced WBBC has a high porosity of 52.3%, an alkaline pH of 9.0, and a carbon content of 84%, which improved its adsorption capacity. At 120 minutes of contact time, the modified WBBC demonstrated significantly improved adsorption efficiencies of 92.2% for Cd²⁺ and 86.4% Pb²⁺, respectively. On the other hand, the unmodified biochar showed substantially lower adsorption capacities and removal efficiencies ($\leq 20\%$) than Cd²⁺ and Pb²⁺, which had equilibrium adsorption capacities (Q_e) of 1.4 mg/g and 1.3 mg/g, respectively. Adsorption was shown to follow the pseudo-second-order model ($R^2 > 0.99$), with chemisorption as the dominant adsorption/removal mechanism. Statistical analysis revealed that the modification significantly enhanced adsorption efficiency. These results highlight the potential of modified WBBC as a practical, affordable, and sustainable solution for treating heavy metal-contaminated wastewater from food processing, especially in regions with limited resources.

Keywords: Adsorption kinetics, Heavy metals, Modified activated carbon, Optimization, WBBC

INTRODUCTION

Every aspect of life depends on water, although increases in pollution, population growth, and climate change continue to threaten freshwater ecosystems and resources, thereby causing significant and long-term ecological disasters (Aleruchi *et al.*, 2023; du Plessis, 2022; Ijanu *et al.*, 2024). Wastewater from industries, including those in the food processing sector, such as maize flour mills, often contains harmful chemicals from machinery corrosion, processing additives, and raw material impurities (Ijanu *et al.*, 2023; Kolawole *et al.*, 2024; Sharma *et al.*, 2022). Thus, the presence of contaminants of effluents has become an urgent environmental problem with notable consequences for human health and eco-systems. Recent studies reveal that over 80% of wastewater globally is released into the environment without sufficient

treatment, leading to the pollution of aquatic bodies with hazardous substances (Li *et al.*, 2023; Samal *et al.*, 2022).

However, the introduction of heavy metals from both biological and human-caused environmental sources has raised significant concerns, as these metallic elements are readily adsorbed into cellular membranes, leading to various life-threatening diseases in humans and aquatic creatures even at low concentrations (Aziz & Kareem, 2023; Singh *et al.*, 2024; Ullah *et al.*, 2020; Wu *et al.*, 2024; Zhang *et al.*, 2023). Additionally, nutrient-rich effluents contribute to eutrophication by creating algal blooms that deplete water bodies of oxygen, resulting in dead zones where aquatic life cannot survive. This loss of water quality hinders the resilience of aquatic ecosystems and deprive

aquatic life of their habitat (Dhirendra, 2018; Sahu *et al.*, 2024; Vantarakis, 2021).

Adsorption techniques are among the most commonly used approaches for eliminating metallic substances from wastewater. Activated carbon, due to its high surface area and pore size, has been extensively utilized as an adsorbent for many contaminants (Fang *et al.*, 2023). However, its performance can be significantly enhanced through modification approaches, thereby improving its adsorption capacity and selectivity for specific pollutants (Shrestha *et al.*, 2021; Zhao *et al.*, 2022). In recent studies, Singh *et al.* (2023) and Zhu *et al.* (2022) reported the use of modified activated carbon for lead and cadmium ion removal. However, a search of the available previous literature did not yield a study explicitly targeting maize flour mill effluent. Existing findings generally focus on synthetic wastewater, leaving a gap in understanding how modification techniques might enhance adsorption in real-world agricultural wastewater. For this reason, this study attempts to fill in this gap by looking at the modification of activated carbon using phosphoric acid (H_3PO_4) for enhanced adsorption of lead and cadmium ions from maize flour mill effluent.

In contrast to prior studies that focus on traditional adsorption isotherm performance, this study analyses the effects of contact time, pH, adsorbent dosage, and other parameters on the kinetics and mechanisms of adsorption in real waste liquids. By implementing modification methods, the study seeks to improve the adsorption capacity of activated carbon for the selected heavy metals. Ultimately, this research aims to contribute to the development of cost-effective and ecologically friendly technologies for treating wastewater contaminated with selected heavy metals from maize flour mills. The research aims to mitigate the environmental impacts of Pb^{2+} and Cd^{2+} by optimizing their removal efficiency, thereby contributing to healthier ecosystems and safer water supplies for communities.

MATERIALS AND METHODS

Study Area

This research was conducted at a maize flour mill in Godiya Miyeti Estate, Takur, Dutse, Jigawa State, Nigeria, located at 11.76°N, 9.34°E, at an elevation of 460 meters above sea level. According to the 2022 population census (Adeleye *et al.*, 2019; Amoo *et al.*, 2024), Dutse city had a population of 431,800 and experiences a tropical savanna climate with distinct wet and dry seasons.

Collection and Analysis of Wastewater Samples

Wastewater samples were collected using the grab sampling technique outlined by Khan *et al.* (2023). This method involved obtaining samples directly from the mill's effluent discharge point to ensure accuracy and representativeness (Figure 1). Prior to sample collection, pre-cleaned 5-litre polyethylene bottles were thoroughly rinsed with the wastewater to minimize contamination and maintain sample integrity. The wastewater sample collected were subsequently transported to the Environmental Science Laboratory at Federal University Dutse, Nigeria, and preserved at 4°C, following APHA (2017) recommendations. One litre of the sample was used to investigate physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), and heavy metal concentrations such as cadmium and lead. Prior to sample analysis, buffer solutions with pH values of 4.0, 7.0, and 10.0 were used to calibrate a calibrated digital pH meter (HANNA HI 2211). A Jenway 4510 conductivity meter calibrated with a 1413 $\mu S/cm$ KCl solution was used to measure electrical conductivity, and an HM Digital COM-100 meter calibrated with a 342 ppm NaCl standard was used to measure TDS as described by Amoo *et al.* (2023). Samples were acidified with concentrated HNO_3 ($pH < 2$) and digested by wet digestion to perform heavy metal analysis. A flame Atomic Absorption Spectrophotometer (PerkinElmer Analyst 400) was used to filter and analyze the digested samples. Using external calibration with approved standard solutions, the concentrations of cadmium and lead were measured at their respective wavelengths, and all measurements were taken both before and after the activated carbon treatment, as reported by Muhammad *et al.* (2024) and Qaseem *et al.* (2021).

Biochar Preparation and Modification

Wood-based biomass biochar (WBBC) was chosen over other agricultural waste-derived biochar types due to its relatively easy modification, high carbon content, and renewability. Wood biochar has a large porous structure and improved surface reactivity owing to chemical activation, which enhances its suitability for heavy metal adsorption (Krstić, 2021). Wood biomass was sourced from the Dutse plank market, thoroughly washed, and sun-dried for 72 hours, after which a 350 g sample was placed in a clean dry crucible, capped with a glass lid, and pyrolyzed at a temperature of 600 for one hour, 30 minutes in an SX-2.5-10 muffle furnace, as described by Li *et al.* (2023). The resulting

biochar was cooled in an inert atmosphere at 25°C, then crushed and sieved to optimize particle size. Finally, the biochar was steam

activated at 700°C for 30 minutes to improve its porosity and adsorption performance.



Figure 1. Mill effluent discharge point from the study area

Chemical Activation Process

To enhance adsorption capacity, the biochar samples were subjected to phosphoric acid (H₃PO₄) activation, during which they were impregnated with 50% H₃PO₄ at a 1:2 weight ratio (biochar:acid). The mixture was then agitated constantly for 12 hours at room temperature to attain adequate impregnation. After soaking, the biochar was charred at 700°C for 30 minutes to improve its porosity. Finally, it was rinsed with deionized water to remove residual acid, dried at 105°C, and sieved ($\leq 100 \mu\text{m}$) for adsorption evaluations.

Wastewater Characterisation

The pH level of the sample was measured with a calibrated pH meter, and moisture content was assessed by drying at 105°C until a uniform weight was achieved. Ash concentration was evaluated by heating at 550°C to remove organic elements, leaving only mineral remnants. Electrical conductivity (EC) was examined using a conductivity meter to estimate ionic strength and dissolved ions. Total carbon content was measured with a carbon analyzer using standard protocols outlined by Yargicoglu *et al.* (2015).

Characterisation of Modified Biochar

A digital pH meter was used to examine the pH of the biochar, and the ash concentration was determined by incinerating the biochar at 550°C to remove organic components. Using Brunauer-Emmett-Teller (BET) surface area analysis of nitrogen adsorption-desorption isotherms at 77 K, the porosity and surface properties were investigated, yielding specific surface area, pore volume, and pore-size distribution. The water-displacement method was also used to estimate total pore volume, following the methods

outlined by Liu *et al.* (2016), thereby validating the BET findings.

Batch Adsorption Experiments

Batch experiments were conducted in 250-mL Erlenmeyer flasks to evaluate the effects of contact time (0-120 min), pH (2, 4, 6, and 8), and adsorbent dosage (5, 10, and 15 g) on heavy metal removal. Each experiment involved 100 mL of wastewater, with wood-based biomass biochar (WBBC) added at the selected dosage. Samples were filtered using Whatman No. 4 filter paper (pore size 20-25 μm) before analysis and evaluated for remaining metal concentrations using PerkinElmer AAS Pinnacle 900H as described by Liu *et al.* (2022). To investigate the influence of pH on adsorption, the wastewater pH was adjusted to the desired level using 0.1 M HCl or 0.1 M NaOH before adding 10 g of biochar to each treatment batch. After 90 minutes of agitation, residual metal concentrations were measured to identify the appropriate pH for adsorption, following the approaches documented by Hasnain & Ngaini (2024). Removal efficiency and adsorption capacity were computed using the methods of Karthik *et al.* (2024).

Adsorption Kinetics and Mechanism

Adsorption kinetics were investigated using the pseudo-first-order, pseudo-second-order, and Weber-Morris intraparticle diffusion models to understand the adsorption behavior of Pb²⁺ and Cd²⁺. The pseudo-second-order model (Equation 1) was utilized to find the adsorption rate constant (Karthik *et al.*, 2024):

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

where t is time (min), q_t is the adsorption capacity at time t (mg/g), q_e is the equilibrium

adsorption capacity (mg/g), and k_2 is the pseudo-second-order rate constant (g/mg·min). The adsorption capacity was estimated using Equation (2):

$$q_t = \frac{(C_0 - C_t)V}{m} \quad (2)$$

where V is the volume (L), m is the biochar mass (g), C_0 is the initial metal concentration, and C_t is the concentration at time t . To evaluate the adsorption mechanism, BET analysis was used to determine the influence of surface area, and the pH effect was examined to assess ion exchange and electrostatic attraction in metal removal.

Data Analysis

Data analysis was conducted using SPSS to assess the reliability of the experimental results. One-way Analysis of variance was used to analyze the

effects of key experimental parameters (contact time, pH, and adsorbent dosage) on heavy metal removal efficiency. The regression assessments were used to determine the best-fitting adsorption model, with R^2 values used to evaluate model accuracy, as described by Revellame *et al.* (2020).

RESULTS

Physicochemical Properties of Maize Mill Wastewater

The physicochemical analysis of industrial wastewater from maize flour mills highlights its potential environmental impact and suitability for discharge. The results are presented in Table 1.

Table 1. Physicochemical properties of maize mill industrial wastewater

Parameter	Value	WHO	NESREA
pH	6.74	6.5-8.5	6.5-8.5
EC (µS/cm)	80.7	< 250	Not specified
Temperature (°C)	32.3	25 - 30	25 - 30
Odour	Putrid	Not specified	Not specified
Colour	Milky white	Colourless	Not specified
TDS (mg/L)	250 mg/L	< 500	< 2000
Lead (mg/L)	0.022	0.01	0.01
Cadmium (mg/L)	0.023	0.03	0.01

Biochar Characterisation

Characterizing wood-based biomass biochar (WBBC) provides crucial insights into its suitability for heavy-metal adsorption. The results are presented in Table 2.

Table 2. Physicochemical characteristics of WBBC

Parameter	Values
pH	9.0
Moisture content (%)	11.2
Ash content (%)	6
Porosity (%)	52.3
EC (µS/cm)	1200
Total carbon (%)	84

Influence of Metal Ion Properties on Adsorption Capacity

Their ionic radii and electronegativity influenced the adsorption efficiency of Cd^{2+} and Pb^{2+} . Lead (Pb^{2+}) has a larger ionic radius (119 pm) compared to cadmium (Cd^{2+}) (97 pm), which affects the diffusion of these ions into the biochar pores. Additionally, the

electronegativity of Pb^{2+} (2.33) is higher than Cd^{2+} (1.69), leading to stronger interactions with biochar surface functional groups. The difference in adsorption capacities between Cd^{2+} and Pb^{2+} is thus attributed to these physicochemical properties, as supported by the data in Table 3.

Table 3. Heavy metal concentrations before and after adsorption using WBBC at different dosages

Heavy Metal	Initial Conc. (mg/L)	Removal at 5g WBBC (mg/L)	Removal at 10g WBBC (mg/L)	Removal at 15g WBBC (mg/L)
Cadmium (Cd^{2+}) ion	0.023	0.0028	0.0018	0.0012
Lead (Pb^{2+}) ion	0.022	0.0035	0.0025	0.0018

Adsorption Performance

Influence of Contact Time, pH, and Adsorbent Dosage

The study demonstrated that WBBC adsorption efficiency for cadmium ion (Cd^{2+}), and lead ion (Pb^{2+}) was influenced by these operational parameters. The effect of contact time (Table

4) showed that removal efficiency increased with increasing contact time. The pH of the solution (Table 5) played a critical role in determining adsorption efficiency. The adsorbent dosage (Table 6) further influenced heavy metal removal efficiency.

Table 4. Effect of contact time on metal removal efficiency (%)

Contact Time (min)	Cd Removal (%)	Pb Removal (%)
0	71.74	63.64
10	78.26	70.45
30	84.78	77.27
60	89.13	81.82
120	92.17	86.36

Table 5. Effect of pH on metal removal efficiency (%)

pH	Cd Removal (%)	Pb Removal (%)
0.0	0.0	0.0
2.0	10.20	6.4
4.0	30.8	22.3
6.0	45.8	36.5
8.0	55.2	46.0

Table 6. Effect of adsorbent dose on metal removal efficiency (%)

Adsorbent Dose (g)	Cd^{2+} Removal (%)	Pb^{2+} Removal (%)
5	35.20	28.14
10	50.62	42.88
15	60.48	52.10

Adsorption Kinetics and Equilibrium Studies

Kinetic modeling established that adsorption followed the pseudo-second-order model, suggesting chemisorption as the dominant mechanism. Additionally, the Weber-Morris model revealed intraparticle diffusion an additional rate-limiting step.

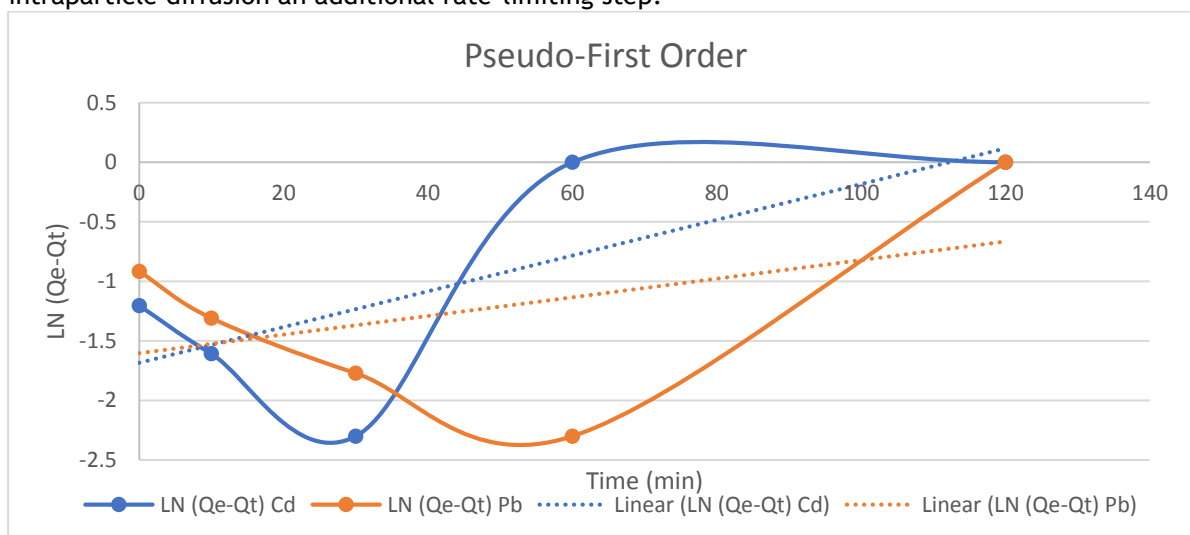


Figure 3. Pseudo-first order kinetic model for cadmium (Cd^{2+}) and lead (Pb^{2+}) adsorption

Table 7. Adsorption kinetics and equilibrium parameters for cadmium (Cd²⁺) removal

Time (min)	C ₀ (mg/L)	C _e (mg/L)	Q _t (mg/g)	Q _e (mg/g)	1/Q _t	t/Q _t (m.g/mg)	% Rem.	Opt. Dose	WW (L)	Q _e -Q _t	LN(Q _e -Q _t)	t ^{0.5}
0	2.3	0.65	1.1	1.4	0.91	0	71.7	15	0.1	0.3	-1.204	0
10	2.3	0.50	1.2	1.4	0.83	8.33	78.3	15	0.1	0.2	-1.609	3.16
30	2.3	0.35	1.3	1.4	0.77	23.08	84.8	15	0.1	0.1	-2.302	5.48
60	2.3	0.25	1.4	1.4	0.71	42.86	89.1	15	0.1	0	0	7.75
120	2.3	0.18	1.4	1.4	0.71	85.71	92.2	15	0.1	0	0	10.95

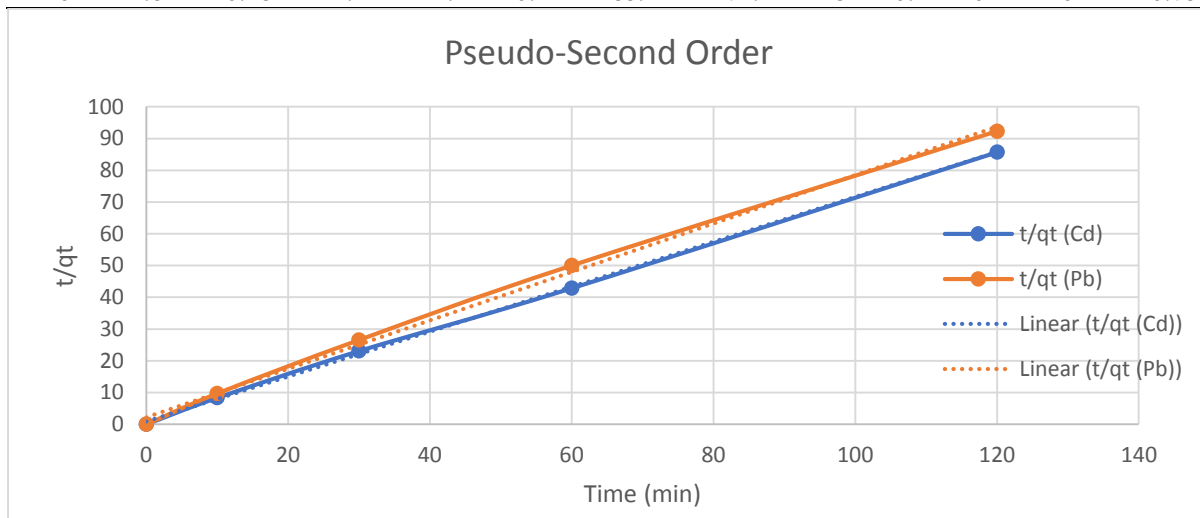


Figure 4. Pseudo-second order kinetic model for cadmium (Cd²⁺) and lead (Pb²⁺) adsorption

Table 8. Adsorption kinetics and equilibrium parameters for lead (Pb²⁺) removal

Time (min)	C ₀ (mg/L)	C _e (mg/L)	Q _t (mg/g)	Q _e (mg/g)	1/Q _t	t/Q _t (m.g/mg)	% Rem.	Opt. Dose	WW (L)	Q _e -Q _t	LN(Q _e -Q _t)	t ^{0.5}
0	2.2	0.80	0.90	1.3	1.11	0	63.6	15	0.1	0.4	-0.916	0
10	2.2	0.65	1.03	1.3	0.97	9.71	70.5	15	0.1	0.27	-1.309	3.16
30	2.2	0.50	1.13	1.3	0.88	26.55	77.3	15	0.1	0.17	-1.772	5.48
60	2.2	0.40	1.20	1.3	0.83	50.0	81.8	15	0.1	0.1	-2.302	7.75
120	2.2	0.30	1.30	1.3	0.77	92.31	86.4	15	0.1	0	0	10.95

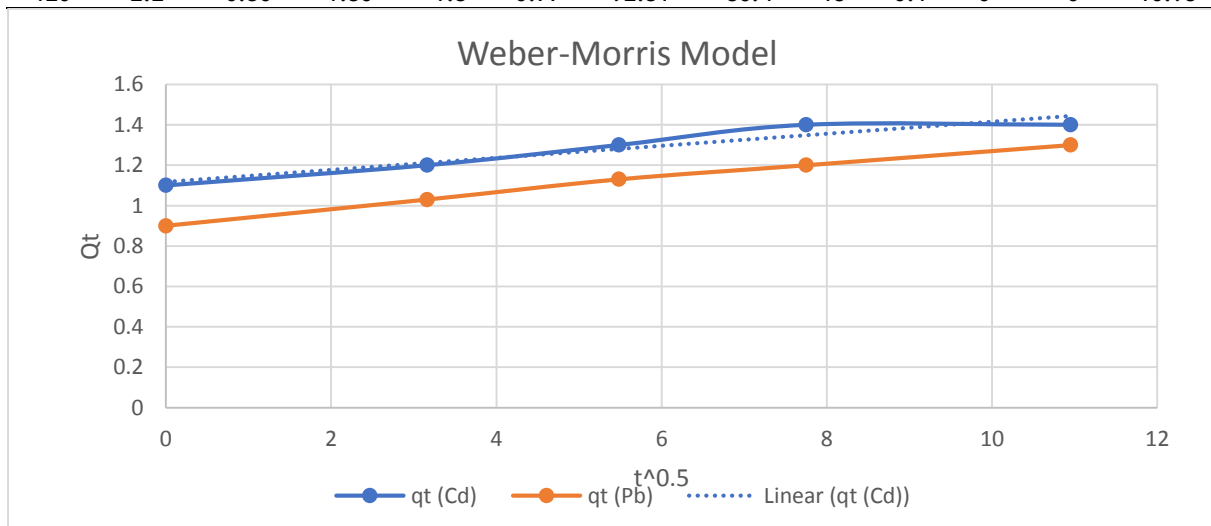


Figure 5. Weber-Morris kinetic model for cadmium (Cd²⁺) and lead (Pb²⁺) adsorption

Table 9. Kinetic model parameters for Cd²⁺ and Pb²⁺ adsorption

Response	Pseudo-first order model			Pseudo-second order model			Weber-Morris model		
	Q _e (mg/g)	R ²	K ₁ (g/m.min)	Q _e (mg/g)	R ²	K ₂ (g/m.min)	Q _e (mg/g)	R ²	K ₃ (g/m.min)
Cd ²⁺	66.67	0.5117	7483.42	1.4	0.9996	1.70	33.56	0.9208	1258.04
Pb ²⁺	128.21	0.186	26356.38	1.3	0.9976	3.60	27.32	0.9933	680.58

Table 10. ANOVA Results for Adsorption Efficiency

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Value	p-Value
Between Groups (pH)	12.35	3	4.12	18.76	0.002**
Between Groups (Dosage)	15.89	2	7.95	22.43	0.001**
Within Groups	5.42	12	0.45	-	-

$p < 0.05$ indicates a statistically significant difference.

Table 11. t-test Results Comparing Modified vs. Unmodified Biochar Adsorption

Adsorbent Type	Mean Adsorption Efficiency (%)	Standard Deviation (SD)	t-Value	p-Value
Modified WBAC	92.5	3.4	5.86	0.004**
Unmodified Biochar	78.3	5.2	-	-

$p < 0.05$ indicates a statistically significant improvement in adsorption using modified WBBC.

DISCUSSION

Physicochemical Properties of Wastewater

The physicochemical parameters of the wastewater investigated in this study indicate substantial pollution. The wastewater temperature (32.3°C) exceeded WHO and NESREA limits (25-30°C), which could reduce dissolved oxygen and accelerate organic matter decomposition, similar to concerns in agro-industrial effluents (Thankgod *et al.*, 2024). Its putrid odour and milky white colour suggest significant contamination from suspended organic matter and microbial activity as illustrated in Table 1. The pH (6.74) of the sample is within the permissible 6.5-8.5 range (Table 1), enabling biological treatment processes, consistent with research on cassava mill (Lawal *et al.*, 2019) and abattoir wastewater (Hussaini *et al.*, 2023). The electrical conductivity (80.7 µS/cm) analyzed was below the WHO acceptable limit (250 µS/cm), indicating a lower ion concentration than in ore processing wastewater (225-361 µS/cm) as reported earlier by Ayedun *et al.* (2023). The outcome of the total dissolved solids sample at 250 mg/L indicates that the maize flour mill wastewater contains relatively low levels of dissolved inorganic and organic substances, indicating minimal salinity and a lower potential for long-term environmental harm, as also reported by Petre *et al.* (2023) in their study.

Biochar Characterisation

The characterization of WBBC highlighted noteworthy potential for metal adsorption. The pH of 9.0 indicates alkalinity and strengthens the adsorption of metal ions such as Pb²⁺ and Cd²⁺. This finding corroborates recent studies that emphasize the benefits of similar pH values in enhancing toxic metal removal (Wang *et al.*, 2023). The moisture content of 11.2% confirms significant water retention, which could hinder

pore accessibility. Compared to previous research, this value aligns with the acceptable water range for adsorption efficiency. The ash concentration of 6% showed the presence of inorganic residues, which is consistent with the support's ability to hinder or enhance adsorption depending on its composition. The porosity of 52.3% is high, confirming that the biochar has a well-developed pore structure, which supports greater interaction with metal ions and, consequently, improved adsorption (Pet *et al.*, 2024). The electrical conductivity of 1200 µS/cm, in tandem with a high total carbon content of 84%, supports the already established theory that WBBC can efficiently adsorb pollutants by providing sufficient surface area and active sites for ion exchange and adsorption (Elewa *et al.*, 2023). The analysis of variance results presented in Table 10 revealed statistically significant differences in the adsorption efficiency of Pb²⁺ and Cd²⁺ under varying pH levels and adsorbent dosages, as indicated by the p-values of 0.002 and 0.001, respectively ($p < 0.05$). These low p-values indicate that both pH and dosage significantly affect the adsorption performance of the modified activated carbon. This finding highlighted the critical role of pH in determining metal-ion speciation and surface charge interactions during adsorption. The significant influence of dosage further supports the assertion that increased active surface area enhances metal uptake, consistent.

Comparison of Modified and Unmodified Biochar

Comparing modified and unmodified biochar demonstrated that the modification approach significantly improved the adsorption efficiency for both Pb²⁺ and Cd²⁺. The equilibrium adsorption capacity (Q_e) for Cd²⁺ and Pb²⁺ with modified activated carbon was 1.4 mg/g and 1.3 mg/g, respectively. In contrast, the unmodified

biochar exhibited substantially lower Q_e values, with Cd^{2+} and Pb^{2+} removal efficiencies barely exceeding 20% and 15%, respectively. Furthermore, the independent t-test results in Table 11 show a statistically significant difference ($p = 0.004$) in the mean adsorption efficiency between the modified activated carbon (92.5%) and the unmodified biochar (78.3%). This implies that chemical modification of the biochar significantly improved its adsorptive capacity, likely due to increased surface functional groups and porosity. The combined statistical evidence supports the optimization strategy applied in this study, confirming that both adsorbent dosage and pH adjustment are critical factors for maximizing removal efficiency. These findings substantiate the efficacy of the modified biochar as a superior low-cost material for treating maize flour mill wastewater contaminated with Pb^{2+} and Cd^{2+} . These results accord with recent research by Tang *et al.* (2018) and Zheng *et al.* (2019), which have repeatedly demonstrated that altering biochar leads to considerable increases in its adsorption capacity.

Adsorption Efficiency and Mechanisms

The modification of activated carbon improved the adsorption of both Pb^{2+} and Cd^{2+} ions, with 92.2% and 86.4% removal, respectively, at 120 minutes of contact time. This performance is in line with other studies showing that chemically modified activated carbons exhibit comparable removal efficiencies for these metals (Raninga *et al.*, 2022; Zhu *et al.*, 2022). The enhanced removal efficiency can be attributed to the improved availability of adsorption sites following the surface modification. A similar structure was observed in the research of Ciesielezyk *et al.* (2015), and Jha *et al.* (2021), where surface modification of activated carbon resulted in a more rapidly initial uptake of metal ions, which eventually attained equilibrium. This trend was corroborated by the pseudo-second-order kinetic model, which best represented the adsorption process,

demonstrating that chemisorption was the major mechanism governing metal ion removal, supported by the formation of surface complexes and ion exchange. The discrepancy in the adsorption capabilities of Pb^{2+} and Cd^{2+} is likely related to the variation's ionic attributes of these metals. Pb^{2+} has a larger ionic radius and stronger interaction with surface functional groups, making it more readily adsorbed onto the modified carbon surface than Cd^{2+} . This result corroborates the findings of Hussain *et al.* (2023) and Mariana *et al.* (2021), who observed that metal ion size and charge distribution possess vital roles in their adsorption onto modified surfaces.

CONCLUSION AND RECOMMENDATIONS

Conclusively, this study demonstrates that modified WBBC considerably enhances the removal of Pb^{2+} and Cd^{2+} from maize mill effluent compared to unmodified biochar, and the physicochemical evaluation of WBBC revealed its high porosity and surface functionalization, which contributed to increased metal ion binding. The adsorption process was substantially impacted by contact time, pH, and adsorbent dosage, with modified WBBC obtaining optimal removal efficiencies of 92.2% (Pb^{2+}) and 86.4% (Cd^{2+}). Statistical analysis confirmed that both pH and dosage had significant effects on adsorption performance, with ANOVA p-values of 0.002 (pH) and 0.001 (dosage), while a t-test showed a significant improvement in adsorption efficiency for modified WBBC compared to unmodified biochar ($p = 0.004$). The adsorption mechanism followed pseudo-second-order kinetics, suggesting that chemisorption played a critical role in metal ion intake. Given these findings, further research should explore long-term stability, reusability, policy-driven adoption, and cost-effectiveness of improved WBBC in large-scale wastewater treatment systems.

REFERENCES

- Adeleye, A. O., Yalwaji, B., Shiaka, G. P., Amoo, A. O., & Udochukwu, C. C. (2019). Bacteriological quality of fresh-cut ready to eat vegetables sold in Dutse Market North-west, Nigeria. *FUW Trends on Science and Technology Journal (FTSTJ)*, 4(1), 054-057. [Link]
- Aleruchi, O., Fubara, E., & Otto, B. (2023). Wastewater quality-Its impact on the environment and human physiology: A review. *International Journal of Advance Research and Innovation*, 9, 43-58. [Crossref]
- American Public Health Association (APHA). (2017). *Standard methods for the examination of water and wastewater* (22nd ed.). American Water Works Association & Water Pollution Control Federation. [Link]
- Amoo, A. O., Adeleye, A. O., Madu, I. E., Asaju, C. I., Amoo, N. B., Abdullahi, A. A., & Alabi, I. A. (2023). Impact of slaughterhouse effluents on groundwater quality: Evidence-based

- assessment in Tudun-Wada and Kawo residential suburbs, Kaduna, Nigeria. *Journal of Environmental Issues and Climate Change*, 2(1), 41-50. [\[Crossref\]](#)
- Amoo, A. O., Adeleye, A. O., Bate, G. B., Ijanu, M. E., Adamu, S. B., Asaju, C. I. & Olaitan, I. I. (2024). Microbiological analysis of hawked-cooked food: Evidence from ready-to-eat food vendors in Dutse Ultra-Modern Market, Northwestern, Nigeria. *Tropical Environment, Biology, and Technology*, 2(1), 23-33. [\[Crossref\]](#)
- Ayedun, H., Eje, R. E., & Daudu, O. O. (2023). Industrial wastewater purification using cow bone and sawdust filters. *Nigerian Journal of Chemical Research*, 28(1), 012-024. [\[Crossref\]](#)
- Aziz, K. H. H., & Kareem, R. (2023). Recent advances in water remediation from toxic heavy metals using biochar as a green and efficient adsorbent: A review. *Case Studies in Chemical and Environmental Engineering*, 8, Article 100495. [\[Crossref\]](#)
- Ciesielczyk, F., Bartczak, P., & Jesionowski, T. (2015). A comprehensive study of Cd (II) ions removal utilizing high-surface-area binary Mg-Si hybrid oxide adsorbent. *International Journal of Environmental Science and Technology*, 12(11), 3613-3626. [\[Crossref\]](#)
- Dhirendra, S. (2018). Eutrophication in water by detergents. *International Journal of Advanced Research in Arts, Science, Engineering & Management*, 5(1), 1656-1663. [\[Link\]](#)
- du Plessis, A. (2022). Persistent degradation: Global water quality challenges and required actions. *One Earth*, 5(2), 129-131. [\[Crossref\]](#)
- Elewa, A. M., Amer, A. A., Attallah, M. F., Gad, H. A., Al-Ahmed, Z. A. M., & Ahmed, I. A. (2023). Chemically activated carbon based on biomass for adsorption of Fe(III) and Mn(II) ions from aqueous solution. *Materials*, 16(3), 1251. [\[Crossref\]](#)
- Fang, L., Huang, T., Lu, H., Wu, X. L., Chen, Z., Yang, H., Wang, S., Tang, Z., Li, Z., Hu, B., & Wang, X. (2023). Biochar-based materials in environmental pollutant elimination, H₂ production, and CO₂ capture applications. *Biochar*, 5(1), 42. [\[Crossref\]](#)
- Hasnain, A., & Ngaini, Z. (2024). Designed biochar for heavy metals removal from wastewater. *Advances in Materials for Water Treatment*, 53-64. [\[Crossref\]](#)
- Hussain, D., Khan, S., Alharthi, S., & Khan, T. A. (2023). Insight into the performance of novel kaolinite-cellulose/cobalt oxide nanocomposite as green adsorbent for liquid phase abatement of heavy metal ions: Modelling and mechanism. *Arabian Journal of Chemistry*, 15, 103925. [\[Crossref\]](#)
- Ijanu, E. M., Idris, M., Adeleye, A. O., Amoo, A. O., Mohammed, A. T., & Salihu, Y. S. (2024). Removal of Lead Ion (Pb²⁺) From Synthetic Wastewater Using Sugarcane Bagasse. *Environmental Contaminants Reviews (ECR)* 7(2), 48-50. [\[Crossref\]](#)
- Ijanu, E. M., Miko, A., Adeleye, A. O., Mohammed, A. T., Amoo, A. O., & Idris, M. (2023). Removal of Chromium from Tannery Wastewater Using Modified Corn Cobs. *Environmental Contaminants Reviews (ECR)* 6(1), 41-45. [\[Crossref\]](#)
- Jha, M. K., Joshi, S., Sharma, R. K., Kim, A. A., Pant, B., Park, M., & Pant, H. R. (2021). Surface modified activated carbons: Sustainable bio-based materials for environmental remediation. *Nanomaterials*, 11(11), 3140. [\[Crossref\]](#)
- Karthik, V., Periyasamy, S., Dharneesh, S., Duvakeesh, G. K., Gizaw, D. G., & Vijayashankar, V. (2024). Biochar as a sustainable adsorbent for heavy metal removal from polluted waters: A comprehensive outlook: A review. *Wiley Journal of Chemistry*, 26. [\[Crossref\]](#)
- Khan, S. N., Nafees, M., & Imtiaz, M. (2023). Assessment of industrial effluents for heavy metals concentration and evaluation of grass (*Phalaris minor*) as a pollution indicator. *Heliyon*, 9(9), e20299. [\[Crossref\]](#)
- Kolawole, I. D., Kolawole, G. O., Sanni-manuel, B. A., Kolawole, S. K., Ewansiha, J. U., Kolawole, V. A., & Kolawole, F. O. (2024). Economic impact of waste from food, water, and agriculture in Nigeria: Challenges, implications, and applications—a review. *Discover Environment*, 2(1), 51. [\[Crossref\]](#)
- Krstić, V. (2021). Some effective methods for treatment of wastewater from Cu production. In I. Inamuddin, M. I. Ahamed, & E. Lichtfouse (Eds.), *Water pollution and remediation: Heavy metals* (pp. 313-440). Springer International Publishing. [\[Crossref\]](#)
- Lawal, N., Ogedengbe, K., Adetifa, B., & Anyanwu, G. (2019). Degrading cassava

- mill effluent using aerated sequencing batch reactor with palm kernel shell as medium. *Journal of Degraded and Mining Lands Management*, 6(3), 1737-1745. [\[Crossref\]](#)
- Li, X., Zhang, Y., & Wang, S. (2023). Adsorptive removal of toxic heavy metals from wastewater using biochar-based materials: A review. *Environmental Science and Pollution Research*, 30(1), 1-15. [\[Crossref\]](#)
- Liu, H., Li, P., Qiu, F., Zhang, T., & Xu, J. (2022). The application of eco-friendly Fe-Al bimetallic oxide/biochar adsorbent composites with waste rice husk for removal of arsenic at low concentration. *Journal of Inorganic and Organometallic Polymers and Materials*, 32(1), 122-133. [\[Crossref\]](#)
- Liu, Z., Dugan, B., Masiello, C. A., Barnes, R. T., Gallagher, M. E., & Gonnermann, H. (2016). Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar-sand mixtures. *Journal of Hydrology*, 533, 461-472. [\[Crossref\]](#)
- Mariana, M., Abdul Khalil, H. P. S., Mistar, E. M., Yahya, E., Alfatah, T., Danish, M., & Amayreh, M. (2021). Recent advances in activated carbon modification techniques for enhanced heavy metal adsorption. *Journal of Water Process Engineering*, 43, 102221. [\[Crossref\]](#)
- Muhammad, Z., Ibrahim, Y., Umar, F. S., & Akindehinde, B. A. (2024). Analysis of selected heavy metals and physicochemical properties of irrigation water and soil from Warwade Dam, Dutse LGA, Jigawa State. *Chemistry Search Journal*, 15(1), 238-247. [\[Link\]](#)
- Pet, I., Sanad, M. N., Farouz, M., ElFaham, M. M., El-Hussein, A., Abd El-sadek, M. S., Althobiti, R. A., & Ioanid, A. (2024). Review: Recent developments in the implementation of activated carbon as heavy metal removal management. *Water Conservation Science and Engineering*, 9, 62. [\[Crossref\]](#)
- Petre, A., Ciopec, M., Timofte, D., Iovu, H., Codrici, E., Dima, L., Dinu, S., & Dediu, L. (2023). Effective purification of eutrophic wastewater from the beverage industry using microbubbles. *Water*, 13(24), 3661. [\[Crossref\]](#)
- Qasem, N. A. A., Mohammed, R. H., & Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: A comprehensive and critical review. *npj Clean Water*, 4, 36. [\[Crossref\]](#)
- Raninga, M., Mudgal, A., Patel, V., Patel, J., & Sinha, M. (2022). Modification of activated carbon-based adsorbent for removal of industrial dyes and heavy metals: A review. *Materials Today: Proceedings*. [\[Crossref\]](#)
- Revellame, E. D., Fortela, D. L., Sharp, W., Hernandez, R., & Zappi, M. E. (2020). Adsorption kinetic modeling using pseudo-first order and pseudo-second order rate laws: A review. *Cleaner Engineering and Technology*, 1, 100032. [\[Crossref\]](#)
- Sahu, A. K., Mir, S., Nayak, B., & Baitharu, I. (2024). Chapter 13 - Sustainable management of eutrophication and problems associated with the algal toxin in ponds and lakes of rural areas. In S. Madhav, A. L. Srivastav, S. C. Izah, & E. van Hullebusch (Eds.), *Water resources management for rural development* (pp. 155-170). Elsevier. [\[Crossref\]](#)
- Samal, K., Mahapatra, S., & Ali, M. H. (2022). Pharmaceutical wastewater as emerging contaminants (EC): Treatment technologies, impact on environment and human health. *Energy Nexus*, 6, Article 100076. [\[Crossref\]](#)
- Sharma, P., Gaur, V. K., Gupta, S., Varjani, S., Pandey, A., Gnansounou, E., You, S., Ngo, H. H., & Wong, J. W. C. (2022). Trends in mitigation of industrial waste: Global health hazards, environmental implications and waste derived economy for environmental sustainability. *Science of The Total Environment*, 811, Article 152357. [\[Crossref\]](#)
- Shrestha, R., Ban, S., Devkota, S., Sharma, S., Joshi, R., Tiwari, A. P., Kim, H. Y., & Joshi, M. K. (2021). Technological trends in heavy metals removal from industrial wastewater: A review. *Journal of Environmental Chemical Engineering*, 9(4), 105688. [\[Crossref\]](#)
- Singh, P. K., Kumar, U., Kumar, I., Dwivedi, A., Singh, P., Mishra, S., Seth, C. S., & Sharma, R. K. (2024). Critical review on toxic contaminants in surface water ecosystem: Sources, monitoring, and its impact on human health. *Environmental Science and Pollution Research*, 31(45), 56428-56462. [\[Crossref\]](#)
- Singh, V., Pant, N., Sharma, R. K., Padalia, D., Rawat, P. S., Goswami, R., Singh, P., Kumar, A., Bhandari, P., Tabish, A., & Deifalla, A. M. (2023). Adsorption

- Studies of Pb(II) and Cd(II) Heavy Metal Ions from Aqueous Solutions Using a Magnetic Biochar Composite Material. *Separations*, 10(7), 389. [\[Crossref\]](#)
- Tang, N., Niu, C. G., Li, X. T., Liang, C., Guo, H., Lin, L. S., Zheng, C. W., & Zeng, G. M. (2018). Efficient removal of Cd²⁺ and Pb²⁺ from aqueous solution with amino- and thiol functionalized activated carbon: Isotherm and kinetics modeling. *Science of the Total Environment*, 635, 1331-1344. [\[Crossref\]](#)
- Thankgod, D. O., Anyalogbu, E. A., & Ogidi, O. I. (2024). Physico-chemical properties and species diversity of crustacean zooplankton in Ikarama River, Yenagoa, Bayelsa State, Nigeria. *International Journal of Scientific Research in Biological Sciences*, 11(4). [\[Link\]](#)
- Ullah, M., Nazir, R., Khan, M., Khan, W., Shah, M., Afridi, S. G., & Zada, A. (2020). The effective removal of heavy metals from water by activated carbon adsorbents of Albizia lebeck and Melia azedarach seed shells. *Soil and Water Research*, 15(1), 30-37. [\[Crossref\]](#)
- Vantarakis, A. (2021). Eutrophication and public health. In M. G. Zamparas & G. L. Kyriakopoulos (Eds.), *Chemical Lake Restoration: Technologies, Innovations and Economic Perspectives* (pp. 23-47). Springer International Publishing. [\[Crossref\]](#)
- Wang, B., Lan, J., Bo, C., Gong, B., & Ou, J. (2023). Adsorption of heavy metal onto biomass derived activated carbon: Review. *RSC Advances*, 13, 4275-4302. [\[Crossref\]](#)
- Wu, X., Nawaz, S., Li, Y., & Zhang, H. (2024). Environmental health hazards of untreated livestock wastewater: Potential risks and future perspectives. *Environmental Science and Pollution Research*, 31(17), 24745-24767. [\[Crossref\]](#)
- Yargicoglu, E. N., Sadasivam, B. Y., Reddy, K. R., & Spokas, K. A. (2015). Physical and chemical characterization of waste wood derived biochars. *Waste Management*, 36, 256-268. [\[Crossref\]](#)
- Zhang, P., Yang, M., Lan, J., Huang, Y., Zhang, J., Huang, S., Yang, Y., & Ru, J. (2023). Water quality degradation due to heavy metal contamination: Health impacts and eco-friendly approaches for heavy metal remediation. *Toxics*, 11(10), 828. [\[Crossref\]](#)
- Zhao, J., Wu, Q., Tang, Y., Zhou, J., & Guo, H. (2022). Tannery wastewater treatment: Conventional and promising processes, an updated 20-year review. *Journal of Leather Science and Engineering*, 4(1), 10. [\[Crossref\]](#)
- Zheng, W., Chen, S., Liu, H., Ma, Y., & Xu, W. (2019). Study of the modification mechanism of heavy metal ions adsorbed by biomass-activated carbon doped with a solid nitrogen source. *RSC Advances*, 9, 37440-37449. [\[Crossref\]](#)
- Zhu, L., Yao, Y., Chen, D., & Lan, P. (2022). The effective removal of Pb²⁺ by activated carbon fibers modified by L-cysteine: Exploration of kinetics, thermodynamics, and mechanism. *RSC Advances*, 12(31), 20062-20073. [\[Crossref\]](#)