

Efficiency of Biochar Obtained from Cashew Nut Shells as a Potential Adsorbent of Heavy Metals from Eleyele Dam, Ibadan



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ABSTRACT: Most industrial effluent is characterized with heavy metal contamination and other toxic, non-biodegradable pollutants which can endanger both aquatic life and human health. Traditional treatment methods are often costly and produce harmful secondary waste, highlighting the need for sustainable alternatives. This study explores the use of Cashew-nut Shells (CNS), an abundant agricultural by-product, to produce biochar as a low-cost and effective adsorbent for removing heavy metal ions. Cashew nut shells were pyrolyzed at 600–700 °C and physically activated using superheated steam to enhance porosity and adsorption capacity. The resulting biochar was incorporated into a down-flow filtration column containing sand, biochar, and gravel layers. The collected wastewater from Eleyele Dam, Ibadan, was digested with nitric acid and analyzed using Atomic Absorption Spectrophotometry (AAS). Physicochemical parameters and concentrations of Pb, Cd, and Fe were compared before and after treatment based on National Environmental Standards and Regulations Enforcement Agency (NESREA) standards. Although pH remained slightly acidic, heavy-metal removal efficiencies were 97.14, 64.29 and 43.75% for Fe, Pb and Cd respectively. Post-treatment concentrations of Fe (0.09mg/L) and Cd (0.009) met NESREA effluent discharge standards of <0.01 and 5 mg/L respectively, while Pb reduced from 0.28 to 0.10mg/L, a value higher than 0.05mg/L permissible limit. Physically activated CNS biochar is an efficient and environmentally friendly adsorbent, demonstrating excellent removal of iron and satisfactory reduction of cadmium. Although lead removal was substantial, further optimization such as increased biochar dosage, longer contact time, or multi-stage filtration is required for full compliance with effluent discharge standards.

KEYWORDS: Industrial Effluent, Bio-adsorbent, Cashew-Nut Shell, Down-flow filtration, Heavy metals

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I. INTRODUCTION

Heavy metals enter aquatic environments from both natural processes such as geochemical reactions, breakdown of organic matter and from human activities, particularly industrial discharge (Egbueri and Unigwe, 2020; Ogundipe et al., 2023). As industries, agriculture, transportation, and domestic activities expand, metal contaminants like Pb, Cd, Hg, and As increasingly accumulate in water bodies, threatening aquatic life, human health, and general water quality (Adesiyiyan et al., 2018; Ojelabi et al., 2018).

The World Health Organization has established maximum contaminant or permissible limits for As, Cu, Pb, Cd, Cr, Co, Hg, Ni, and Zn in drinking water at 0.01, 2.5, 0.05, 0.003, 0.05, 0.1, 0.001, 2.0, and 5.0 mg/L, respectively. These metals are non-biodegradable and persist in the environment, causing bioaccumulation, organ damage, reduced reproduction, and elevated cancer risks across species, thereby necessitating a concise remediation approach in lieu of public safety. According to Karim et al. (2023) and Nuithitikul et al. (2025), traditional methods for removing metal ions from effluents, including chemical precipitation, lime coagulation, ion exchange, reverse osmosis, and solvent

extraction, have limitations; among the limitations include insufficient metal removal, high reagent and energy requirements and, production of noxious sludge or waste products that require proper disposal. In addition, these techniques are limited by high costs, technical viability, particularly when used to remove dissolved metals in large volumes of water; they generate large amounts of solid waste.

As reported by Tripathi and Rawat Ranjan, (2015), adsorption remains one of the most efficient, low-cost, and adaptable methods for heavy-metal removal. Highly refined activated carbon, which is an industrial adsorbent is the most widely used adsorbent due to its high porosity and adsorption capacity, but its high cost and limited regenerability restrict large-scale application (Afolabi and Alade, 2015). The trio of Tripathi and Rawat Ranjan. (2015), Crini et al. (2019) and Rammal et al. (2025) identified and evaluated the effectiveness of zeolites, plant powders, wood, polymeric and nano materials for their adsorption characteristic and effectiveness for heavy metal remediation, biochar showed prospect in carbon sequestration, while although activated carbon is reported as been effective, its use has a disadvantage of higher cost and energy intensity. This challenge is encouraging the development of cheaper

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alternatives such as bio-adsorbents or biochar derived from agricultural waste. Bio-adsorbents or biochar offer good surface characteristics, renewability, and environmental friendliness, making them promising substitutes for conventional activated carbon (Fonseca and Oliveira de Deus Junior, 2021). According to Fonseca *et al.* (2021) and Pandey *et al.* (2025) Hunaidah *et al.* (2019) in their research stated that one type of active bio-filter material suitable for use as an absorbent is activated biochar from cashew nutshell.

Biochar can be activated through physical, chemical, or physico-chemical methods to enhance its surface area, porosity, and functional groups for improved pollutant and heavy-metal adsorption. Physical activation uses high temperatures with steam or CO₂ to create extensive pore structures (Inyang *et al.*, 2016), while chemical activation involves use of reagents like KOH, H₃PO₄, HNO₃, or ZnCl₂ that open pores and introduce reactive surface groups. Physico-chemical activation, such as microwave, ultrasound, or hydrothermal-assisted treatment, combines both physical and chemical effects to rapidly enhance pore development and surface functionality. This study therefore having simplicity and alternative product development as its focus employed the use of physical activation of the biochar from cashew nut. This is channeled to ensure an increased efficiency of the biochar making it more effective for environmental applications such as wastewater treatment targeted in this study. Physical activation method is a simple, low-cost, and environmentally friendly method as previously reported (Sajjadi *et al.* 2019; Anerao *et al.* 2022). In physical activation using an oxidizing agent, also named as “gaseous activation”, biochar is exposed to a desired volume of either steam, ozone, carbon dioxide, or air at temperatures usually above 700°C.

II. MATERIALS AND METHODS

The major materials used for this study included CNS residues sourced from the Cocoa Research Institute of Nigeria, distilled water, nitric acid, laboratory glassware, a muffle furnace, pressure-steam activation setup, sieves (250 µm), a filtration column, and, Atomic Absorption Spectrophotometer (AAS). Additional materials included sand, gravel, and other accessories required for column filtration.

A Study area

The Eleyele Dam (Figure 1) is situated upstream on River Ona, in the city of Ibadan within Geographical Coordinates: Latitude 7° 20' – 7° 25'N, and Longitude 3° 51' – 3° 56' E, at an elevation of approximately 125 m above sea level, within a region receiving significant rainfall, with annual averages of around 1500 mm to over 1900 mm. It falls within the Ido LGA of Oyo State, Nigeria. The river is vital to Ibadan's municipality as a primary source of drinking water and irrigation. It supports local livelihoods, offers recreation, and sustains ecological balance. Hence this study is conducted with a view of protecting the river for community health and environmental well-being

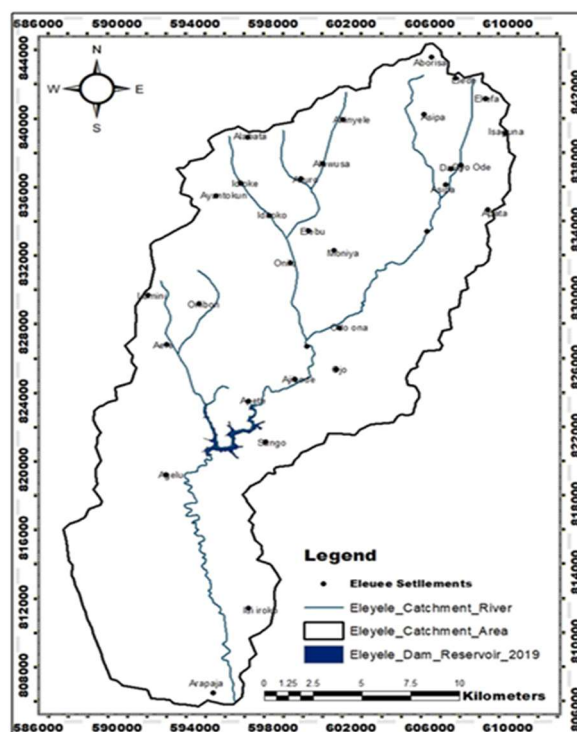
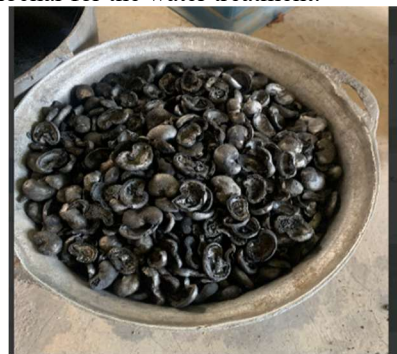


Figure 1: Eleyele Dam on Ona River Source: (Ogundairo *et al.* 2025)

B Production and Activation of Biochar

Cashew-Nut Shells were collected from Cocoa Research Institute of Nigeria in a plastic bag. Afterwards, they were cleaned, dried, and subjected to pyrolysis (Figure 2a). This was carried out in a furnace at 600–700°C for one hour as previously reported by Maaoui *et al.* (2025) for agricultural residues, after which the biochar was allowed to cool. Physical activation was achieved by exposing the biochar to superheated steam generated from boiling water in a pressure cooker for 20 minutes. The process of cooling before activation was also carried out in a research by (Bambhaniya and Gojiya, 2025; Chen *et al.* 2025) for temperature control, process stability, to prevent uncontrolled burn off and pore collapse. Following activation, the biochar was cooled and ground (Figure 2b) to a uniform particle size of approximately 250 µm using a laboratory grinder and sieve to ensure uniform size and increased surface area by the resulting biochar for the water treatment.



(a)



(b)

Figure 2 Cashew nut shell biochar: (a) after pyrolysis and (b) after grinding

C Wastewater Collection and Digestion

Wastewater samples were collected from Eleyele Dam, Ibadan. 10 mL of the well-mixed wastewater sample was transferred into a digestion vessel, followed by the addition of 10 mL of concentrated nitric acid (HNO_3). The mixture was heated at 100 °C for 1 h under controlled conditions to facilitate the oxidation of organic matter and solubilisation of metals. After cooling, the digested sample was filtered and diluted to 50 mL, then analyzed using Atomic Absorption Spectrophotometry (AAS) to determine the concentrations of Pb, Cd, and Fe before treatment. The digestion method used in this study corresponds to an open-vessel nitric acid hot-plate digestion, similar to the procedure described in (ISO 15587-2:2002: *Nitric Acid Digestion*.) Tan et al. (2015).

D Filtration Column Setup

A laboratory-scale down-flow filtration column was constructed from acrylic or PVC material as shown in Figure 3, with internal dimensions of 91.44 cm height, 22.86 cm length, and 30.48 cm width as previously report by Kolajo and Mark (2026) for a similar research on wastewater treatment. The column was divided into four compartments separated by perforated plates. From top to bottom, the filter media were arranged as follows: an 8 kg layer of well-graded sand, a 650 g layer of activated CNS (coconut nutshell) biochar as the adsorbent, an 8 kg layer of well-graded gravel, and a bottom collection chamber fitted with a dispensing tap. A total of 3 L of wastewater was introduced into the column. The treated effluent (2.25 ± 0.12 L) was collected after an average filtration time of 10 min 34 ± 16 s, yielding a flow rate of 0.213 L/min. The corresponding hydraulic retention time (HRT) was approximately 89.7 minutes (~1.5 h).



Figure 3 Filtration column

E Treatment Analysis

The filtered effluent was re-analyzed using AAS to quantify the remaining concentrations of Pb, Cd, and Fe, allowing for evaluation of the adsorption efficiency of the activated CNS biochar. Equation 1 to 5 were used to calculate the adsorption properties of activated carbon similar to what was reported by Hunaidah et al., (2019) ; Fonseca and Oliveira de Deus Junior, (2021);

1. Adsorbed concentration:

$$L_t = L_{aw} - L_{ak} \quad (1)$$

where

L_t = the concentration adsorbed (mg/L)

L_{aw} = initial concentration (mg/L)

L_{ak} = final concentration (mg/L)

2. Adsorption capacity:

$$q = \frac{C_0 - C_A}{m} \times V \quad (2)$$

where

q = Adsorption capacity (mg/L)

C_0 = initial concentration (mg/L)

C_A = final concentration (mg/L)

m = activated biochar mass

V = volume of solution (mL)

3. Adsorption efficiency:

$$\% \text{ adsorbed} = \left| \frac{C_0 - C_A}{C_0} \right| \times 100\% \quad (3)$$

4. Sieve analysis calculations

Uniformity Coefficient

$$C_u = \frac{D_{60}}{D_{10}} \quad (4)$$

where

C_u = Coefficient of Uniformity

D_{60} = particle diameter at which 60% of the soil is finer, and

D_{10} = particle diameter at which 10% of the soil is finer by weight

5. Coefficient of Curvature

$$C_c = \frac{D_{(30)^2}}{D_{10} \times D_{60}} \quad (5)$$

where

C_c = Coefficient of Curvature

D_{30} = particle diameter at which 30% of the soil is finer

III. RESULTS AND DISCUSSION

A Sieve analysis

The sieve analysis of the granite used in this study (Figure 4) indicates that 80% of the particles are greater than 2 mm, and yields C_u of 12.58 well above the typical gravel threshold, and a C_c of 2.94, both values confirming that the granite is well-graded. Similarly, sand sample shows that 79.35% of its particles fall at or below ~1 mm, and the computed $C_u = 5$ and $C_c = 1.25$ both fall within accepted ranges ($C_u > 4$, $1 < C_c < 3$), likewise confirming that the sand is well-graded. The particle size distribution analyses provided information on the composition of the filter medium

used in the study and confirmed that both the granite and sand media satisfy the criteria for well-graded materials. This is significant because well-graded granular media exhibit superior packing density, reduced void ratios, and enhanced mechanical interlocking. These properties translate to improved solid-liquid separation, as smaller particles fill interstitial spaces and create more tortuous flow paths for contaminant capture.

The uniformity and curvature coefficients further indicate the absence of gap-grading, thereby minimizing the risk of preferential flow and premature clogging. Consequently, the selected media should promote consistent hydraulic conductivity, prolonged service life, and stable effluent quality throughout the filtration process.

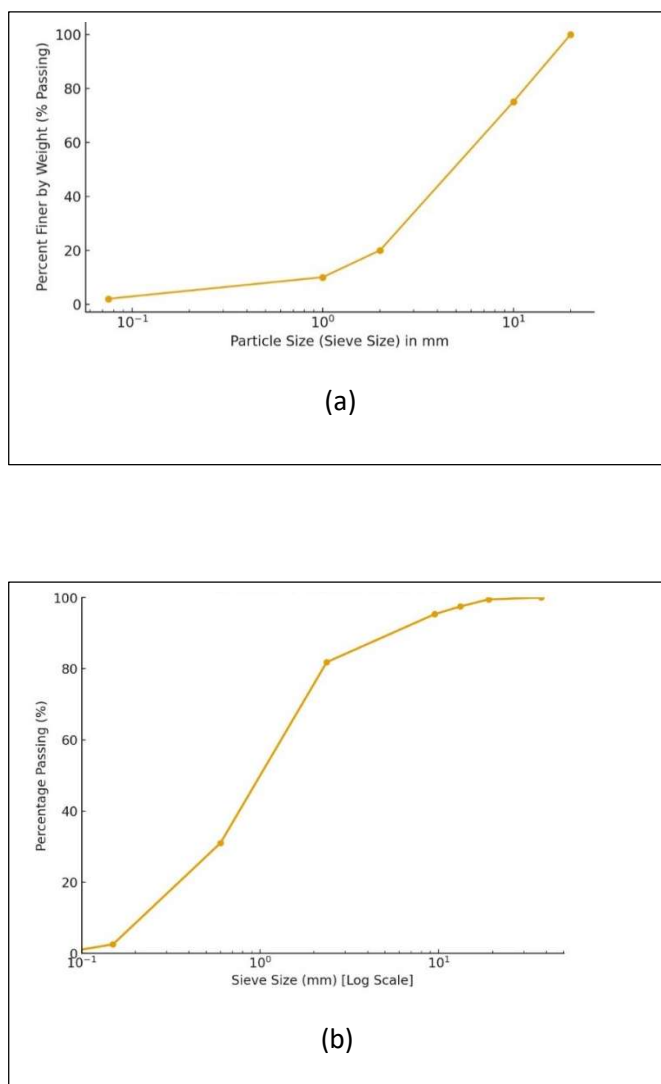


Figure 4 Particle size distribution for (a) Granite
(b) Sand

B Physical parameters

In Table 1, the measured physical parameters of the wastewater were as follows: pH was 5.67 ± 0.05 before treatment and 5.97 ± 0.04 after treatment; Total Dissolved Solids (TDS) decreased from 98.7 ± 2.3 ppm to 91.0 ± 1 ppm,

Electrical Conductivity (EC) reduced from 196.3 ± 2.33 $\mu\text{S}/\text{cm}$ to 188.7 ± 2.7 $\mu\text{S}/\text{cm}$, and turbidity decreased from 5.9 ± 0.3 FNU to 4.6 ± 0.03 FNU following treatment, these values were compared to the NESREA standard for effluent discharge.

The slight increase in pH indicates that the biochar contributed to partial neutralization of the acidic wastewater. In spite of this, the pH remained below the NESREA recommended range of 6.0–9.0.

The reduction in Total Dissolved Solids (TDS) in this study demonstrated that the biochar effectively adsorbed some dissolved ions from the wastewater. A similar observation was reported by Tan et al. (2015), Johnson et al. (2024) where the biochar successfully adsorbed significant amounts of dissolved solids from the petroleum effluent. Both values are well below the NESREA permissible limit of ≤ 2000 mg/L, confirming that the wastewater was already low in dissolved solids and remained compliant after treatment.

Since Electrical Conductivity correlates with the concentration of dissolved ions, this reduction aligns with the observed decrease in TDS, this reduction was also gotten in the research carried out by Johnson et al. (2024). Both values are within the NESREA limit of 1000 $\mu\text{S}/\text{cm}$, indicating that the treated wastewater remains well within acceptable discharge standards. The decrease in turbidity shows that suspended and colloidal particles were effectively removed, and the final turbidity meets the NESREA requirement of ≤ 5 FNU, indicating suitable effluent clarity.

Overall, except for pH, all physical parameters of the treated wastewater met the NESREA standards, demonstrating the effectiveness of biochar in improving the physical quality of the wastewater. Similar findings were

reported by Ojelabi et al. (2018) in their analysis of Eleyele water, where all physical parameters fell within the permissible limits with reference to WHO/SON standard for drinking water.

C Chemical parameters

In Table 2, the initial chemical characteristics of the wastewater before treatment were measured as follows: Chemical Oxygen Demand (COD) was 10 mg/L, lead (Pb) was 0.28 ± 0.03 mg/L, iron (Fe) was 3.15 ± 0.255 mg/L, and cadmium (Cd) was 0.016 ± 0.002 mg/L. These values were compared with the NESREA effluent discharge standards to assess the pollution load entering the treatment system.

The influent COD concentration of 10 mg/L is well below the NESREA limit of ≤ 80 mg/L, indicating a relatively low concentration of oxidizable organic pollutants prior to treatment. However, according to Tan et al. (2015) COD alone does not adequately represent the overall toxicity of wastewater, particularly when heavy metals are present at elevated concentrations. Similar observations have been reported by Ali and Khan. (2019) in wastewater studies where metal contamination posed significant environmental risks despite compliance with COD limits.

Table 1 Physical analysis of wastewater before and after the experiment

Parameter	Unit	Before Treatment	After Treatment	NESREA Standard
pH	-	5.67 ± 0.05	5.97 ± 0.04	6.0-9.0
TDS	Ppm	98.7 ± 2.3	91.0 ± 1	≤ 2000 mg/L
Electrical Conductivity	μ s	196.3 ± 2.33	188.7 ± 2.7	1000/1000
Turbidity	FNU	5.9 ± 0.3	4.6 ± 0.03	5

Table 2 Chemical parameters of the wastewater

Parameter	Unit	Before treatment	After treatment	Removal efficiency(%)	NESREA Standard
COD	mg/L	10 ± 1.3	-		≤ 80 mg/L
Lead (Pb)	mg/L	0.28 ± 0.03	0.10 mg/L	64.29	≤ 0.05 mg/L
Iron (Fe)	mg/L	3.15 ± 0.255	0.09 mg/L	97.14	≤ 5 mg/L
Cadmium (Cd)	mg/L	0.016 ± 0.002	0.009 mg/L	43.75	≤ 0.01 mg/L

1 Lead

In Figure 5a, Prior to treatment, the concentration of Lead (Pb) in the wastewater was 0.28 mg/L which exceeds the NESREA threshold of ≤ 0.05 mg/L, identifying lead as a major contaminant in the raw wastewater. This finding agreed with the study by Ojelabi et al. (2018), who reported elevated Pb concentrations ranging from 0.2 – 0.3mg/L in surface waters of Eleyele Reservoir, Nigeria. Lead is a persistent and non-biodegradable heavy metal with serious ecological and human health implications, including neurotoxicity, kidney damage, and bioaccumulation in aquatic organisms as stated by (Tan et al. 2015; Ali et al. 2019).

After treatment the concentration decreased to 0.10 mg/L. This corresponds to a net removal of 0.18 mg/L and a removal efficiency of 64.29%. The substantial reduction indicates that the cashew-nut-shell biochar exhibited a strong affinity for lead ions, resulting in effective Pb adsorption. The relatively large ionic radius of Pb^{2+} and its strong tendency to form stable interactions with carbonaceous surfaces likely contributed to the high removal efficiency observed. This finding is consistent with previous studies by Tan et al. (2015) reporting the strong affinity of carbon-based adsorbents for lead ions. Inyang, et al. (2016) also stated that

the observed performance was probably due to factors like pH and development of pore sizes during pyrolysis and also the presence of oxygen-containing functional groups. According to a related study by Hunaidah et al. (2019), Pb removal reached very high values under optimized conditions (acidic pH 6 and 200-mesh particle size), with removal efficiencies approaching >90%. Gustavo and Affonso. (2018) also discovered that Pb removal depended strongly on the type of chemical activation: H_2SO_4 -modified CNS achieved 88%, H_2O_2 and in natural around 50–54%, and NaOH-modified showed only 34%.

Physically activated biochar achieved moderate Pb removal, similar to untreated or H_2O_2 -activated biochar in Gustavo and Affonso. (2018), but it is lower than fully optimized chemically activated samples in both studies. The difference is mainly due to chemical activation, finer particle size, and optimized pH conditions that enhance adsorption sites and surface functional groups. The final concentration of Pb (0.10 mg/L) is higher than the NESREA permissible limit for effluent discharge, indicating a need for optimization of the biochar for Lead adsorption.

2 Cadmium

In Figure 5b, The influent Cd concentration of 0.016 ± 0.002 mg/L slightly exceeds the NESREA limit of ≤ 0.01 mg/L, indicating cadmium as another pollutant of concern. According to (Gustavo and Affonso. 2018; Ali et al. 2019), Cadmium is highly toxic even at low concentrations and is

classified as a carcinogen capable of causing kidney dysfunction, bone demineralization, and long-term ecological damage.

After treatment, Cadmium concentration reduced to 0.009 mg/L, giving 43.75% removal efficiency. Cadmium naturally exhibits weaker interaction with carbon-based adsorbents due to its smaller ionic radius and relatively high hydration energy, which makes it less easily attracted to adsorption surfaces. Gustavo and Affonso. (2018) in their research discovered that cadmium adsorption increased significantly with chemical activation: NaOH-modified CNS reached 99%, H₂O₂ 87%, H₂SO₄ 85%, while in natura biochar removed only 69%. Similarly, Ihsanullah et al. (2015) reported that cadmium(II) adsorption onto acid-modified carbon-based adsorbents followed pseudo-second-order kinetics and Langmuir isotherm behavior, with maximum adsorption capacities ranging from 1.22 to 2.02 mg/g depending on the adsorbent type. The relatively lower adsorption efficiency of Cd²⁺ was attributed to its high hydration energy and weaker surface interactions compared to other heavy metals.

Zhang et al. (2021) also reported that Cd²⁺ adsorption onto sulfur (S) and iron (Fe) (S/Fe) co-modified biochar followed pseudo-second-order kinetics and Langmuir isotherm behavior, with a maximum adsorption capacity of 71.79 mg/g. The modification of corn stover biochar with sulfur and iron significantly improved its performance, yielding a capacity nearly ten times higher than that of unmodified biochar. The superior efficiency was attributed to synergistic mechanisms including Cd-S mineral precipitation, surface complexation with functional groups, and ion exchange. The physically activated biochar performed lower than both chemically activated and in natura biochar in their study, likely due to fewer active sites and lower surface area. The removal achieved in this study, therefore, demonstrates that the biochar has potential for cadmium remediation but would require optimization such as chemical activation, increased biochar mass, or extended contact time to significantly outperform the current level.

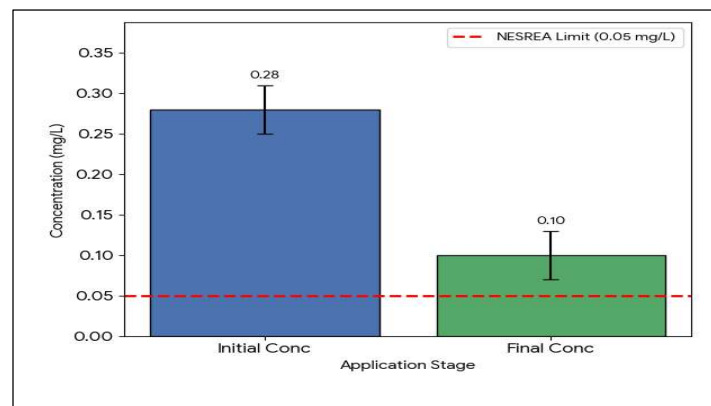
The metal removal efficiencies followed the sequence Fe (97.14%) > Pb (64.29%) > Cd (43.75%), indicating that the cashew-nut-shell biochar exhibited varying affinities toward the different metal ions. These variations can be attributed primarily to differences in ionic radius, hydration energy, prevailing pH conditions, and the nature and availability of surface functional groups on the biochar. The marked reductions in iron, lead, and cadmium concentrations after filtration through the biochar column further confirm the effectiveness of the cashew-nut-shell biochar as a viable adsorbent for the treatment of heavy-metal-contaminated wastewater.

3 Iron

In Figure 5c, The initial Fe concentration of 3.15 ± 0.255 mg/L falls within the NESREA permissible limit of ≤ 5 mg/L. Although compliant with discharge standards, iron at this concentration may still cause aesthetic problems, sediment deposition, pipe clogging, and interference with downstream treatment processes if left untreated as stated by Tchobanoglous and Burton. (2015).

After treatment, the concentration of iron dropped to 0.09 mg/L, translating to very high removal efficiency of 97.14%. Strong adsorption occurred via electrostatic attraction, Fe(OH)₃ precipitation, and complexation with oxygen groups. Fe²⁺/Fe³⁺ ions interact favorably with carbonaceous surfaces, leading to efficient uptake. Similarly, Ghasemi et al. (2015) investigated the adsorption of Fe²⁺ onto chemically activated walnut-shell carbon and reported a maximum removal efficiency of 96.2% at a pH of 4.5 and temperature of 313 K, with adsorption capacities reaching 34.16 mg/g. The adsorption process followed pseudo-second-order kinetics and was best described by the Langmuir isotherm, indicating monolayer chemisorption. Iron removal was attributed to electrostatic attraction, surface complexation with oxygen-containing functional groups, and partial Fe(OH)₃ precipitation. These findings are consistent with the high Fe removal efficiency observed in the present study using cashew-nut shell biochar. Similar trends have also been documented in studies using biochar from other agricultural wastes such as coconut shells, rice husks, and corn cobs as done by Wu et al. (2016).

Mopoung et al. (2015) investigated Fe³⁺ adsorption using KOH-activated tamarind seed carbon in a fixed-bed column system and reported relatively low adsorption capacities ranging from 0.0069 to 0.019 mg/g at initial iron concentrations of 5–20 mg/L. Although adsorption increased under alkaline conditions, the limited performance was attributed to the very low BET surface area (2.72 m²/g) and pore blockage by potassium compounds formed during activation. In contrast, the present study achieved substantially higher iron removal efficiency using physically activated cashew-nut shell biochar, highlighting the strong affinity of iron for carbonaceous surfaces when adequate porosity and surface functionality are present. The final concentration of 0.009mg/L was well below NESREA limits, indicating full compliance, these results confirm cashew-shell biochar's strong suitability for Fe-rich wastewater.



(a)

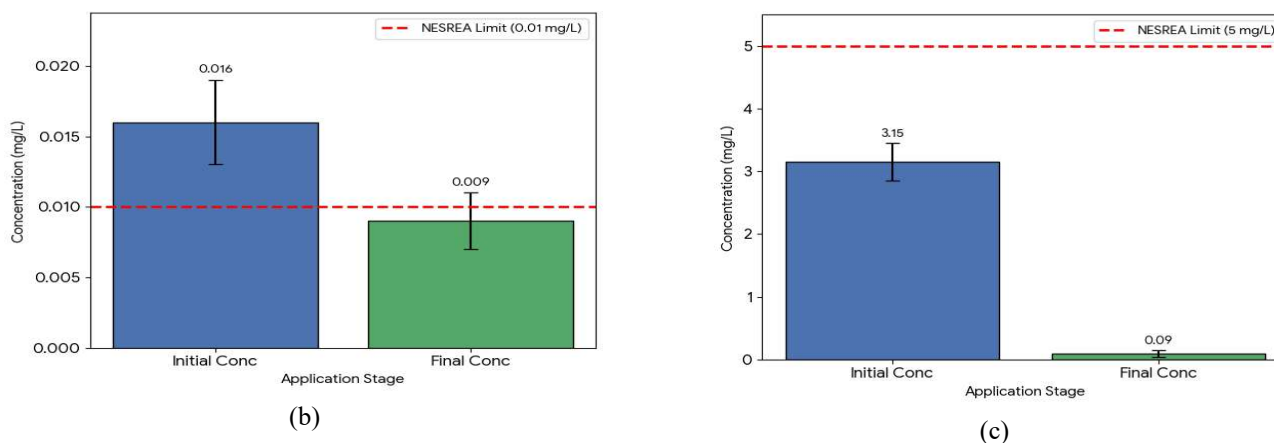


Figure 5 The Initial and final concentration of (a) Lead, (b) Cadmium and (c) Iron

IV CONCLUSION

The physically activated cashew nut shell biochar demonstrated high potential as a low-cost adsorbent for heavy metal removal. Iron (Fe) removal was exceptionally high at 97.14%, reducing the concentration to 0.09 mg/L, which is well below the < 5 mg/L standard. Lead (Pb) saw a significant 64.29% reduction, but its final concentration of

0.10 mg/L was still above the strict < 0.05 mg/L standard. Cadmium (Cd), despite the lowest removal (43.75%), was reduced to 0.009mg/L, achieving compliance with the nation < 0.01mg/L standard. The biochar proved effective for Fe and satisfactory for Cd, but further optimization is required to achieve full compliance for Pb.

AUTHOR CONTRIBUTIONS

The project was conceptualised, designed and finetune by both O.O. Kolajo and V.D. Dada. The original manuscript was written by V.D. Dada under the supervision of O.O. Kolajo. Both authors agreed to the final draft of the manuscript.

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