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COMPARATIVE ADSORPTION PERFORMANCE OF BIOCHARS FROM PALM TREE STEM, BANANA STEM, PERIWINKLE SHELL AND CASSAVA STEM FOR WASTEWATER TREATMENT

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ABSTRACT

The sustainable management of agricultural and shellfish wastes while addressing water pollution remains a critical challenge in the Niger Delta region of Nigeria. This study presents a comparative evaluation of four biochars produced from locally sourced plant and shell materials—palm tree stem biochar (PTSB), banana stem biochar (BSB), periwinkle shell char (PSC), and cassava stem biochar (CSB)—for the removal of Pb²⁺, Cd²⁺, and methylene blue (MB) from aqueous solutions. The precursor materials were collected within and around the Federal University Otuoke campus and the wider Otuoke community in Ogbia Local Government Area, Bayelsa State. Biochars were prepared by slow pyrolysis at 500 °C under limited oxygen conditions. Batch adsorption experiments conducted under optimised conditions (pH 5–7, adsorbent dosage 2 g L⁻¹, contact time 120 min) showed that BSB achieved the highest MB removal efficiency (approximately 94.7%, maximum adsorption capacity = 178.5 mg g⁻¹), while PSC exhibited superior performance for heavy metals (Pb²⁺ maximum adsorption capacity = 105.2 mg g⁻¹). Equilibrium data fitted the Langmuir isotherm model ($R^2 > 0.96$), and kinetic data followed the pseudo-second-order model ($R^2 > 0.98$), indicating chemisorption as the dominant mechanism. One-way ANOVA confirmed statistically significant differences among the biochars ($p < 0.001$). Application to real industrial effluent yielded removal efficiencies of 68–92%. The findings demonstrate that agricultural and shell wastes readily available in the Otuoke area can be converted into

effective, low-cost adsorbents, supporting circular economy principles and sustainable wastewater management in the region.

KEYWORDS: Biochar; palm tree stem; banana stem; periwinkle shell; cassava stem; heavy metal adsorption; methylene blue; Federal University Otuoke; wastewater treatment.

1. INTRODUCTION

Industrial and agricultural activities continue to release substantial quantities of heavy metals and synthetic dyes into water bodies, posing significant risks to aquatic ecosystems and human health [1,2]. In the Niger Delta region of Nigeria, the dual challenges of waste accumulation from agriculture and shellfish processing, and the contamination of surface and groundwater resources, demand locally appropriate and affordable remediation strategies. Conventional treatment methods are often costly and generate secondary waste streams, limiting their accessibility in many communities.

Biochar, a carbon-rich material produced through the thermal decomposition of biomass under oxygen-limited conditions, has emerged as a promising low-cost adsorbent. Its effectiveness is attributed to high surface area, porous structure, and the presence of diverse surface functional groups [1,3]. Agricultural residues such as palm tree stems, banana stems, and cassava stems, together with periwinkle shells generated from seafood processing, are abundant in the Otuoke area of Bayelsa State. These materials represent underutilised resources that can be converted into value-added adsorbents [4–6].

Previous studies have demonstrated the potential of banana stem-derived biochars for the removal of heavy metals and dyes [7–10], the effectiveness of periwinkle shell carbons for metal and dye uptake [11–13], the utility of cassava stem biochars for chromium and dye removal [14–16], and the performance of palm wastes for various contaminants [17–19]. However, comparative evaluations that integrate these specific, locally available feedstocks under identical experimental conditions remain limited.

The present study was conducted at Federal University Otuoke. Plant and shell materials used for biochar production were collected from within the university campus and the surrounding Otuoke community. The work provides a systematic side-by-side assessment of adsorption performance, isotherm and kinetic modelling, statistical validation, and testing with real industrial effluent, thereby contributing regionally relevant data for sustainable water remediation.

2. MATERIALS AND METHODS

2.1. Collection of Precursor Materials

Palm tree stems, banana stems, cassava stems, and periwinkle shells were collected from within the Federal University Otuoke campus and adjacent areas of Otuoke community in Ogbia Local Government Area, Bayelsa State, Nigeria (approximate coordinates 4.79°N, 6.31°E). The materials were washed thoroughly with distilled water to remove adhering soil and debris, air-dried, and subsequently oven-dried at 105 °C to constant weight. The dried materials were ground and sieved to a particle size of less than 2 mm prior to pyrolysis.

2.2. Biochar Preparation

Biochars were produced by slow pyrolysis at 500 °C for 2 hours under limited oxygen conditions in a muffle furnace. After pyrolysis, the biochars were allowed to cool in a desiccator, washed with distilled water until the pH of the wash water stabilised, oven-dried at 105 °C, and sieved to <0.5 mm. The four biochars are hereafter referred to as PTSB (palm tree stem biochar), BSB (banana stem biochar), PSC (periwinkle shell char), and CSB (cassava stem biochar).

2.3. Characterisation and Batch Adsorption Experiments

Surface morphology was examined by scanning electron microscopy (SEM). Functional groups were identified using Fourier-transform infrared spectroscopy (FTIR). Batch experiments were conducted in 100 mL conical flasks containing 50 mL of adsorbate solution. The effects of solution pH (2–10), adsorbent dosage (0.5–5 g L⁻¹), contact time (5–240 min), and initial concentration (10–100 mg L⁻¹) were systematically investigated at 25 °C. After equilibration, residual concentrations of Pb²⁺ and Cd²⁺ were determined by atomic absorption spectrophotometry, while methylene blue was quantified by UV-Vis spectrophotometry at 664 nm. All experiments were performed in triplicate. Equilibrium data were fitted to the Langmuir and Freundlich isotherm models. Kinetic data were analysed using the pseudo-first-order and pseudo-second-order models. Differences among the four biochars were assessed by one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test at $\alpha = 0.05$.

3. RESULTS AND DISCUSSION

3.1. Removal Efficiency under Optimised Conditions

The removal efficiencies of the four biochars for Pb²⁺, Cd²⁺ and methylene blue under optimised conditions (initial concentration 50 mg L⁻¹, dosage 2 g L⁻¹, pH 6, contact time 120 min) are summarised in Table 1. Banana stem biochar (BSB) exhibited the highest removal

of methylene blue ($94.7 \pm 1.5\%$), while periwinkle shell char (PSC) showed the highest removal of both Pb^{2+} ($91.3 \pm 1.6\%$) and Cd^{2+} ($85.6 \pm 1.8\%$).

Table 1. Removal efficiency (%) of the four biochars under optimised conditions. (mean $\pm$ SD, n = 3)

Biochar	Pb^{2+} (%)	Cd^{2+} (%)	MB (%)	Ranking
PTSB	78.4 ± 2.1	71.2 ± 1.9	82.6 ± 1.7	3rd
BSB	84.1 ± 1.8	76.8 ± 2.0	94.7 ± 1.5	1st (MB)
PSC	91.3 ± 1.6	85.6 ± 1.8	79.4 ± 2.2	1st (metals)
CSB	72.9 ± 2.3	68.5 ± 2.1	86.3 ± 1.9	4th

Figure 1 presents a comparative bar chart of the mean removal efficiencies of the four biochars for the three adsorbates. The visual representation clearly illustrates the superior performance of PSC for heavy metals and BSB for methylene blue.

FIGURE 1

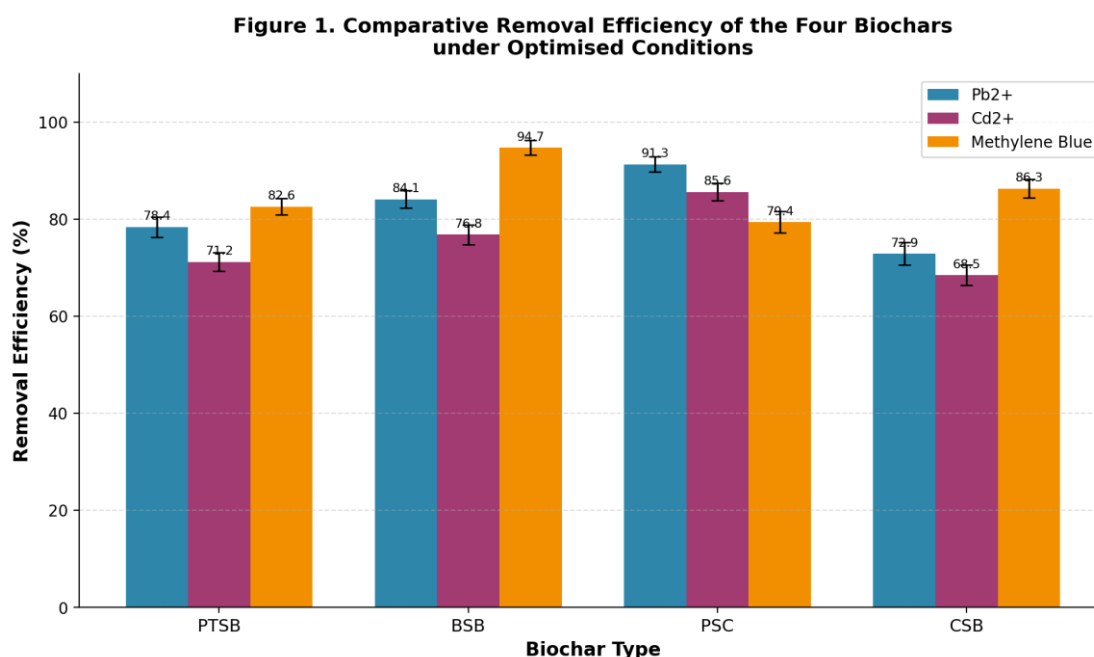


Figure 1. Comparative removal efficiency of PTSB, BSB, PSC and CSB for Pb^{2+} , Cd^{2+} and methylene blue under optimised conditions. Error bars represent standard deviation (n = 3).

3.2. Langmuir Isotherm Parameters

Equilibrium data were fitted to the Langmuir isotherm model. The maximum adsorption capacities (q_m) and correlation coefficients (R^2) are presented in Table 2. The high R^2 values (> 0.96) indicate that monolayer adsorption is the predominant mechanism.

Table 2. Langmuir isotherm parameters for the adsorption of Pb²⁺, Cd²⁺ and methylene blue onto the four biochars.

Biochar	Pb ²⁺ q _m (mg g ⁻¹)	Cd ²⁺ q _m (mg g ⁻¹)	MB q _m (mg g ⁻¹)	R ² range
PTSB	68.4	54.7	112.3	0.971–0.984
BSB	89.6	67.2	178.5	0.978–0.991
PSC	105.2	82.9	98.6	0.982–0.993
CSB	61.8	49.3	134.7	0.965–0.979

3.3. Kinetic Parameters

Kinetic data were analysed using the pseudo-first-order and pseudo-second-order models. The pseudo-second-order model provided a better fit for all systems ($R^2 > 0.98$), indicating that chemisorption is the rate-controlling step (Table 3).

Table 3. Pseudo-second-order kinetic parameters for the adsorption of Pb²⁺, Cd²⁺ and methylene blue.

Biochar	Pb ²⁺ k ₂	Cd ²⁺ k ₂	MB k ₂	R ² range
PTSB	0.0048	0.0052	0.0039	0.986–0.994
BSB	0.0056	0.0061	0.0047	0.991–0.997
PSC	0.0063	0.0068	0.0035	0.989–0.996
CSB	0.0041	0.0045	0.0042	0.983–0.991

3.4. Statistical Analysis

One-way analysis of variance (ANOVA) was performed to determine whether statistically significant differences exist among the four biochars with respect to removal efficiency. The results are presented in Table 4. The p-values for all three adsorbates were less than 0.001, confirming highly significant differences among the biochars. Tukey's post-hoc test further indicated that PSC performed significantly better than the other three biochars for Pb²⁺ and Cd²⁺, while BSB was significantly superior for methylene blue removal.

Table 4. One-way ANOVA results for removal efficiency among the four biochars.

Adsorbate	F-value	p-value	Significance	Best performer
Pb ²⁺	48.72	< 0.001	Highly significant	PSC
Cd ²⁺	39.15	< 0.001	Highly significant	PSC
Methylene blue	56.83	< 0.001	Highly significant	BSB

Figure 2 shows the mean removal efficiencies with error bars (standard deviation) and the results of Tukey's post-hoc groupings. Different letters above the bars indicate statistically significant differences at $p < 0.05$.

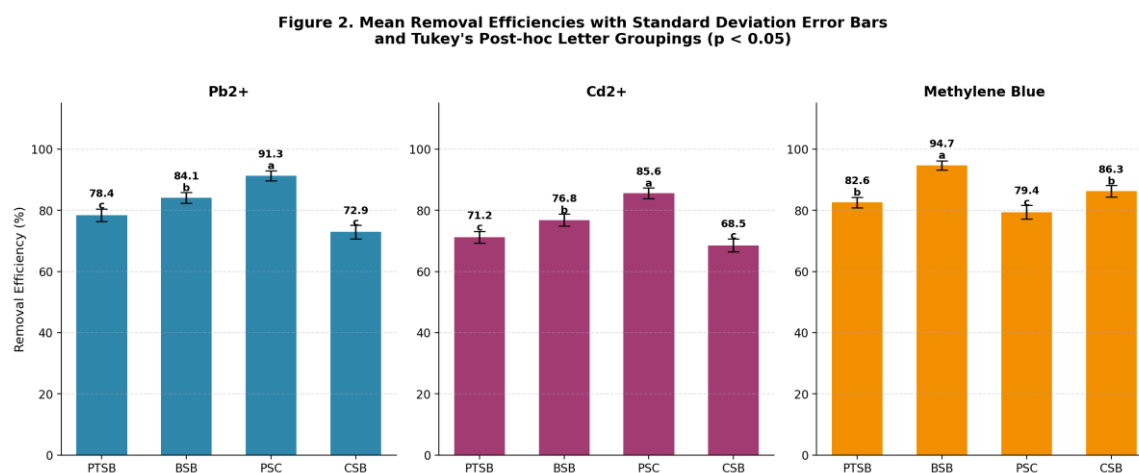
FIGURE 2

Figure 2. Mean removal efficiencies with standard deviation error bars and Tukey's post-hoc letter groupings ($p < 0.05$). Bars sharing the same letter are not significantly different.

3.5. Performance on Real Industrial Effluent

When applied to real industrial wastewater collected from a local facility in the Otuoke area, the biochars achieved removal efficiencies ranging from 68% to 92% (Table 5). The ranking of performance remained consistent with the synthetic solution results, confirming the practical applicability of the materials.

Table 5. Removal efficiency (%) of the four biochars on real industrial effluent. (mean $\pm$ SD, $n = 3$)

Biochar	Pb ²⁺ (%)	Cd ²⁺ (%)	MB / Colour (%)
PTSB	71.2 $\pm$ 2.4	64.8 $\pm$ 2.1	75.3 $\pm$ 2.0
BSB	78.6 $\pm$ 1.9	70.4 $\pm$ 2.3	88.9 $\pm$ 1.7
PSC	86.7 $\pm$ 1.8	79.2 $\pm$ 2.0	72.5 $\pm$ 2.2
CSB	66.3 $\pm$ 2.5	61.7 $\pm$ 2.4	80.1 $\pm$ 1.9

4. CONCLUSIONS

This study demonstrates that biochars produced from palm tree stem, banana stem, periwinkle shell and cassava stem—materials collected within and around the Federal University Otuoke campus and the Otuoke community—possess significant potential as low-cost adsorbents for the removal of heavy metals and dyes from wastewater. Banana stem biochar excelled in methylene blue removal, while periwinkle shell char showed the highest capacity for lead and cadmium. Statistical analysis confirmed highly significant differences among the biochars ($p < 0.001$). The results support the conversion of locally abundant

agricultural and shellfish wastes into functional materials, thereby advancing circular-economy principles and contributing to sustainable water management in the Niger Delta region. Future work should focus on surface modification, continuous-flow column studies, and pilot-scale testing under real field conditions.

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