

Immobilized *Anogeissus leiocarpus* Biomass as a Sustainable Biosorbent for Pb (II) Removal from Aqueous Solution: Adsorption Isotherm and Kinetic Studies

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Abstract

Lead contamination of water remains an environmental and public health concern, motivating the search for affordable, sustainable biosorbents. This study evaluated Pb(II) removal from aqueous solutions using powdered *Anogeissus leiocarpus* stem bark, leaves, and roots immobilized individually and in combination in calcium alginate beads. Batch experiments examined contact time (30–180 min), initial Pb(II) concentration (10–100 mg/L), biosorbent dose (0.25–1.00% w/v), and biosorbent type, alongside no-adsorbent and alginate-only controls. All biosorbents reached equilibrium within 150–180 min. The combined formulation achieved the highest removal efficiency (99.97%) at a dose of 1.00% w/v and an initial Pb(II) concentration of 100 mg/L. Removal efficiencies for stem bark, leaf, and root beads were 99.82%, 99.39%, and 99.11%, respectively, compared with 35.0% for alginate-only beads. Equilibrium data fitted the Freundlich isotherm better than the Langmuir model (Freundlich $R^2 = 0.801$ – 0.9999), consistent with adsorption onto heterogeneous surfaces. Kinetic data closely fitted the pseudo-second-order model across all biosorbents ($R^2 = 1.000$), with calculated equilibrium adsorption capacities closely matching experimental values. Nonzero intercepts in intraparticle diffusion plots suggested an additional contribution from boundary-layer transport. These findings demonstrate high Pb(II) removal by alginate-immobilized *A. leiocarpus* biomass under the tested conditions, particularly when plant parts were combined. The study supports the potential

of these formulations for lead remediation and their further development for wastewater treatment.

Keywords: *Anogeissus leiocarpus*; Pb(II) Biosorption; Calcium Alginate Immobilization; Adsorption Isotherms; Adsorption Kinetics

INTRODUCTION

Because heavy metals like lead, cadmium, mercury, and arsenic are toxic, non-biodegradable, and bioaccumulative, heavy metal pollution of water sources, caused by industrial, agricultural, and domestic activities, poses a serious and ongoing threat to human health and the environment (Ali et al., 2019; Tchounwou et al., 2019). Children are particularly vulnerable to lead (Pb) exposure, which is linked to neurological impairment, developmental delays, and behavioral issues (Sanders et al., 2015; Wang et al., 2022). In many parts of Northern Nigeria, including Adamawa State, water bodies receive lead-containing effluent from domestic, agricultural and small-scale industrial sources, yet conventional water treatment technologies remain costly and inaccessible to many communities, underscoring the need for affordable, locally available alternatives.

By utilizing the functional groups (hydroxyl, carboxyl, and amine) found in lignocellulosic and polyphenolic plant constituents to bind metal ions from solution, biosorption using plant-derived biomass provides an inexpensive, eco-friendly method of heavy metal removal (Nnaji et al., 2022). Rich in tannins, flavonoids, and other phenolic compounds, *Anogeissus leiocarpus* is a *Combretaceae* shrub that is found throughout the West African savanna. It has demonstrated a promising ability to remove heavy metals from raw or chemically modified biomass in earlier research (Adetoro and Ojoawo, 2020; Musa and Yakubu, 2021). While maintaining the biosorbent's inherent adsorption capacity, immobilizing plant biomass within a polymeric matrix like calcium alginate can enhance its mechanical stability, handling, and reusability (Bustos Terrones et al., 2024; Khader et al., 2023).

This study evaluated the capacity of calcium-alginate-immobilized *A. leiocarpus* biomass prepared from stem bark, leaf, root and a combination of all three parts to remove Pb(II) ions from aqueous solution, and characterized the equilibrium and kinetic behaviour of the biosorption process using standard isotherm and kinetic models.

MATERIALS AND METHODS

Plant Material

After being verified by a taxonomist at the Department of Botany at Modibbo Adama University in Yola, the stem bark, leaf, and root of *A. leiocarpus* were gathered from Girei Local Government Area, Adamawa State, Nigeria, cleaned, let to air dry for two weeks, and then milled into a fine powder for use in the creation of biosorbents.

Preparation of Immobilized Biosorbent Beads

To create individual-part beads, powdered leaf, stem bark, and root were mixed with sodium alginate at 0.25%, 0.50%, and 1.00% (w/v). Equal amounts of the three powders were mixed with sodium alginate at the same three concentrations to create a combined-part biosorbent. As a control, an alginate-only blank devoid of any plant material was created. After being hydrated for a full day, each mixture was injected dropwise into a 0.2 M calcium chloride solution using a syringe. After 30 minutes of curing, the beads were rinsed with distilled water to get rid of extra calcium chloride, let to air dry for 48 hours until they reached a constant weight, and then sealed in airtight containers (Bustos Terrones et al., 2024).

Preparation of Lead Solutions

1.5985 g of lead nitrate $[\text{Pb}(\text{NO}_3)_2]$ was dissolved in distilled water to create a 1000 mg/L Pb^{2+} stock solution, which was then acidified with 5 mL of 1% nitric acid. Serial dilution was used to create working solutions of 10, 20, 40, 60, 80, and 100 mg/L. The pH of each solution was then brought to 5.5 using either 0.1 M HCl or NaOH (Abdelhafez et al., 2024).

Batch Adsorption Experiments

In order to perform batch adsorption studies, 50 mL of the produced lead solution was combined with 1.0 g of the suitable biosorbent beads in a 250 mL conical flask that was agitated at 150 rpm and 25 ± 2 °C. The effects of contact time (30–180 minutes), initial lead concentration (10–100 mg/L), biosorbent dose (0.25%, 0.50%, and 1.00%), and biosorbent type (leaf, stem bark, root, combined, and alginate-only) were investigated using a one-factor-at-a-time method while maintaining other parameters at their reference values (1.00% dose, 100 mg/L, 3 hours). Mixtures were filtered through Whatman No. 1 filter paper at the conclusion of each contact period, and the filtrates were stored with a few

drops of strong nitric acid. To differentiate non-adsorptive losses and matrix-level ion exchange from biosorption owing to the plant biomass, an alginate-only control and a no-adsorbent blank (lead solution without beads) were used.

Determination of Residual Lead and Biosorption Performance

Atomic Absorption Spectrophotometry (AAS) was used to detect the residual Pb²⁺ concentration in the filtrates using a calibration curve derived from reference lead solutions. The adsorption capacity at equilibrium (q_e) and at time t (q_t), as well as the percentage removal efficiency, were computed as:

$$\text{Removal Efficiency (\%)} = [(C_0 - C_e) / C_0] \times 100 \quad (1)$$

$$q_e = (C_0 - C_e)V / m \quad (2)$$

$$q_t = (C_0 - C_t)V / m \quad (3)$$

where C_0 , C_e and C_t are the initial, equilibrium and time- t lead concentrations (mg/L) respectively, V is solution volume (L) and m is the dry mass of biosorbent (g).

Adsorption Isotherm and Kinetic Models

The linearized Langmuir ($C_e/q_e = 1/(q_{\max}K_L) + C_e/q_{\max}$) and Freundlich ($\log q_e = \log K_F + (1/n) \log C_e$) isotherm models were fitted to equilibrium data from the initial-concentration experiments (3 h, 1.00% dose). Adsorption favorability under the Langmuir model was evaluated using the dimensionless separation factor $RL = 1/(1 + K_L C_0)$. The pseudo-first-order [$\log(q_e - q_t) = \log q_e - (k_1/2.303)t$], pseudo-second-order [$t/q_t = 1/(k_2 q_e^2) + t/q_e$], and intraparticle-diffusion [$q_t = k_{\text{idt}} t^{0.5} + C$] kinetic models were fitted to contact-time data at 1.00% dosage and $C_0 = 100$ mg/L. The coefficient of determination (R^2) and agreement between estimated and experimental equilibrium capacities were used to assess the model's suitability.

Statistical Analysis

Every experiment was conducted in triplicate, and the mean $\pm$ standard deviation is used to express the results. Significant differences between treatments were tested using a one-way ANOVA, with $p < 0.05$ being considered significant.

RESULTS AND DISCUSSION

Effect of Contact Time

Due to the large concentration gradient and abundance of available vacant active sites at the beginning of the process, lead removal by all four biosorbents increased dramatically during the first 60–90 minutes of contact before gradually increasing to reach equilibrium at about 150–180 minutes (Figure 1). The adsorption rate decreased until equilibrium was reached when binding sites were gradually occupied and the concentration gradient shrank. Alginate immobilization significantly improves lead-removal performance; at an initial concentration of 100 mg/L and 1.00% biosorbent dose, equilibrium removal reached 99.97% for the combined biosorbent, 99.82% for stem bark, 99.39% for leaf, and 99.11% for root. These results exceeded the 65–85% removal reported for unmodified *A. leiocarpus* leaf biomass by Ibrahim et al. (2022) and the 80% benchmark reported by Nnaji et al. (2022).

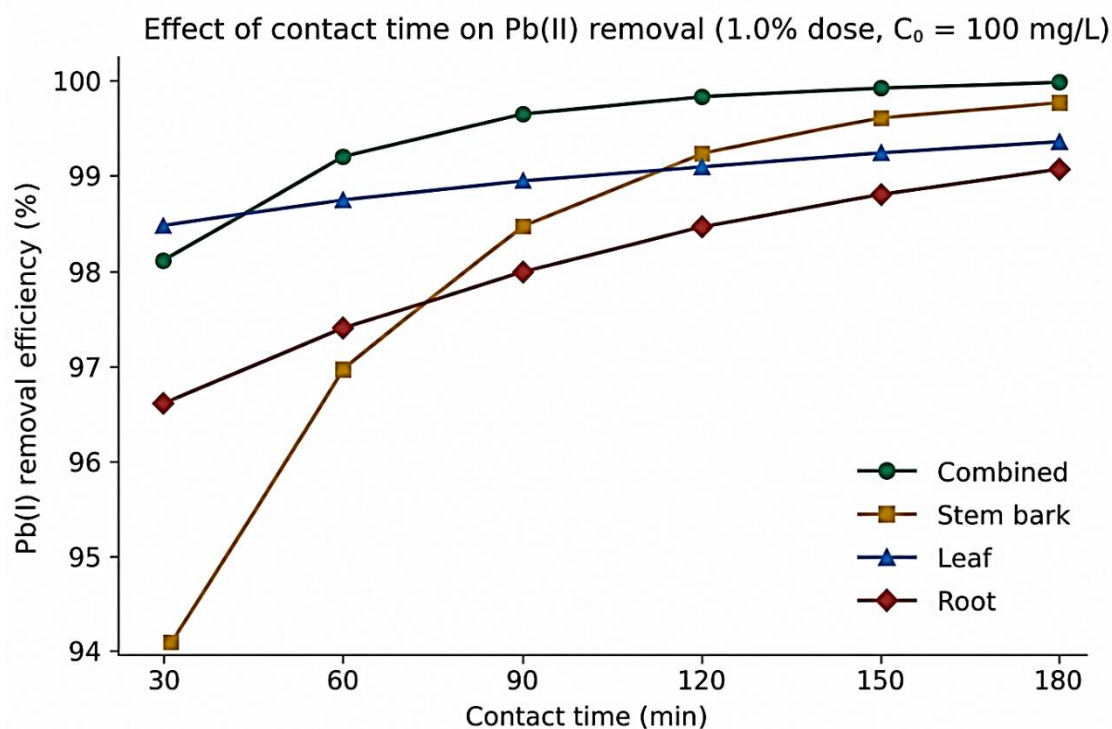


Figure 1: Effect of contact time on Pb(II) removal efficiency for the four biosorbents (1.00% dose, $C_0 = 100$ mg/L).

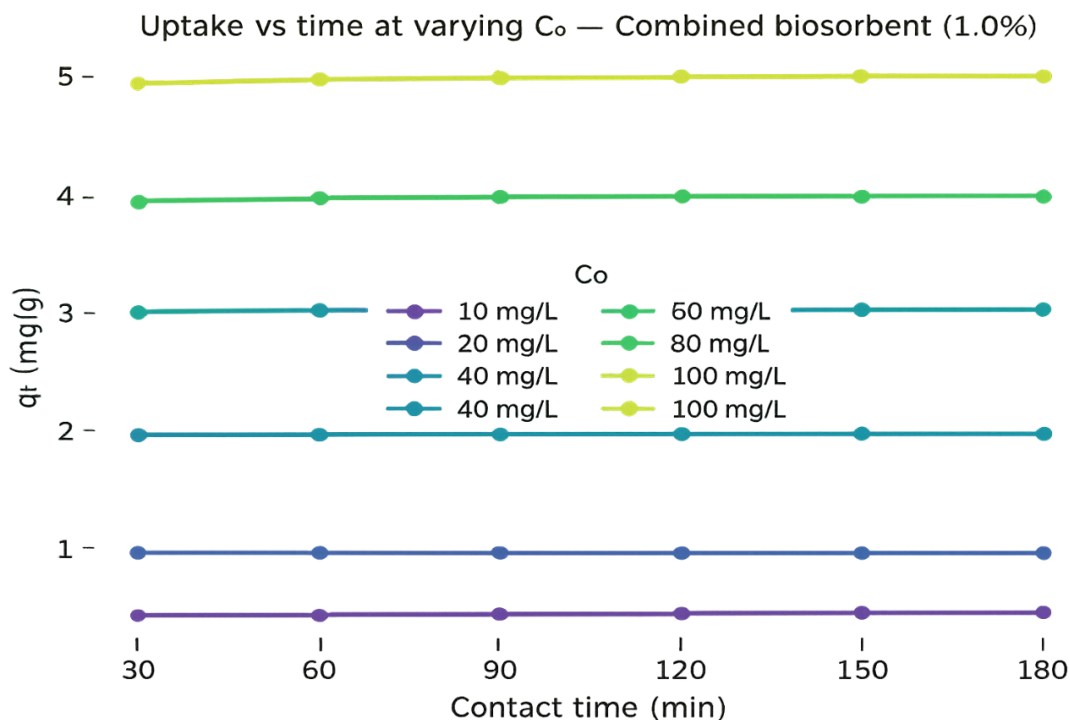


Figure 2: Adsorption capacity (q_t) versus contact time at different initial concentrations for the combined biosorbent (1.00% dose).

Effect of Initial Lead Concentration

While equilibrium adsorption capacity (q_e) increased nearly linearly from roughly 0.48–0.50 mg/g at 10 mg/L to 4.96–5.00 mg/g at 100 mg/L (Figures 3 and 4), indicating the stronger concentration-driven mass-transfer force at higher lead loadings, equilibrium removal efficiency remained consistently high (generally above 95%) throughout the entire concentration range examined (10–100 mg/L). This pattern confirms that the alginate-immobilized biosorbents maintained a strong affinity for Pb^{2+} throughout the concentration window studied. It is similar to findings reported for *A. leiocarpus* stem bark by Adetoro and Ojoawo (2020), citric-acid-modified leaf biomass by Musa and Yakubu (2021), and chitosan-alginate hybrid beads by Ablouh et al. (2019).

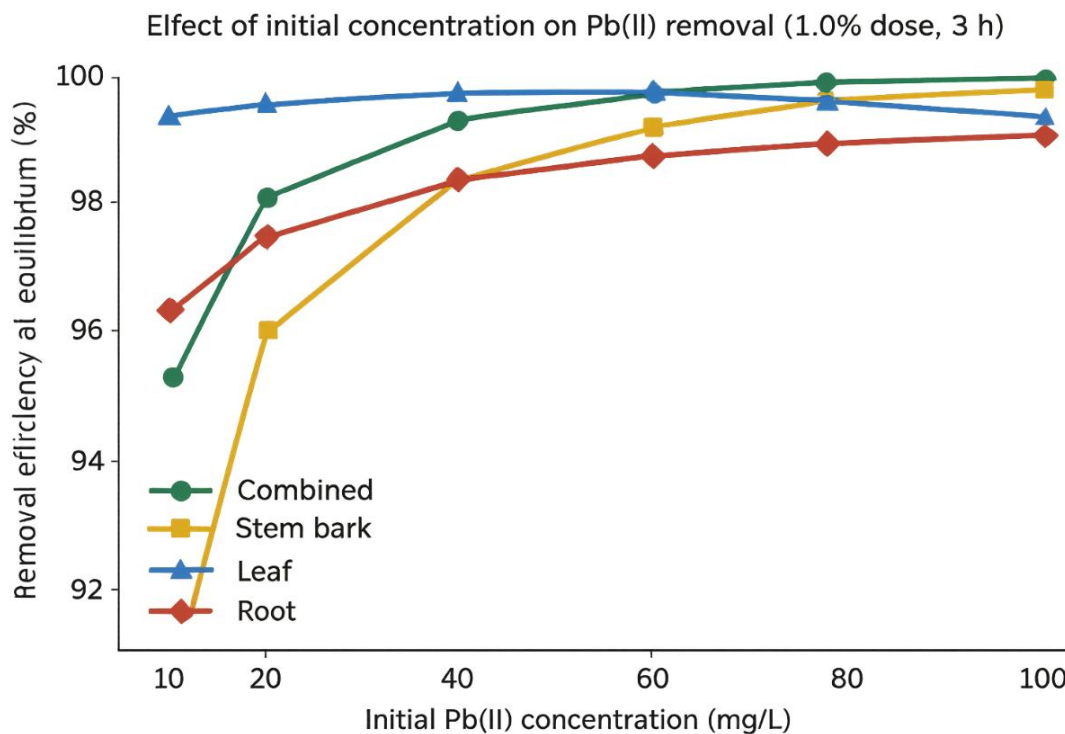


Figure 3: Effect of initial Pb(II) concentration on equilibrium removal efficiency (1.00% dose, 3 h)

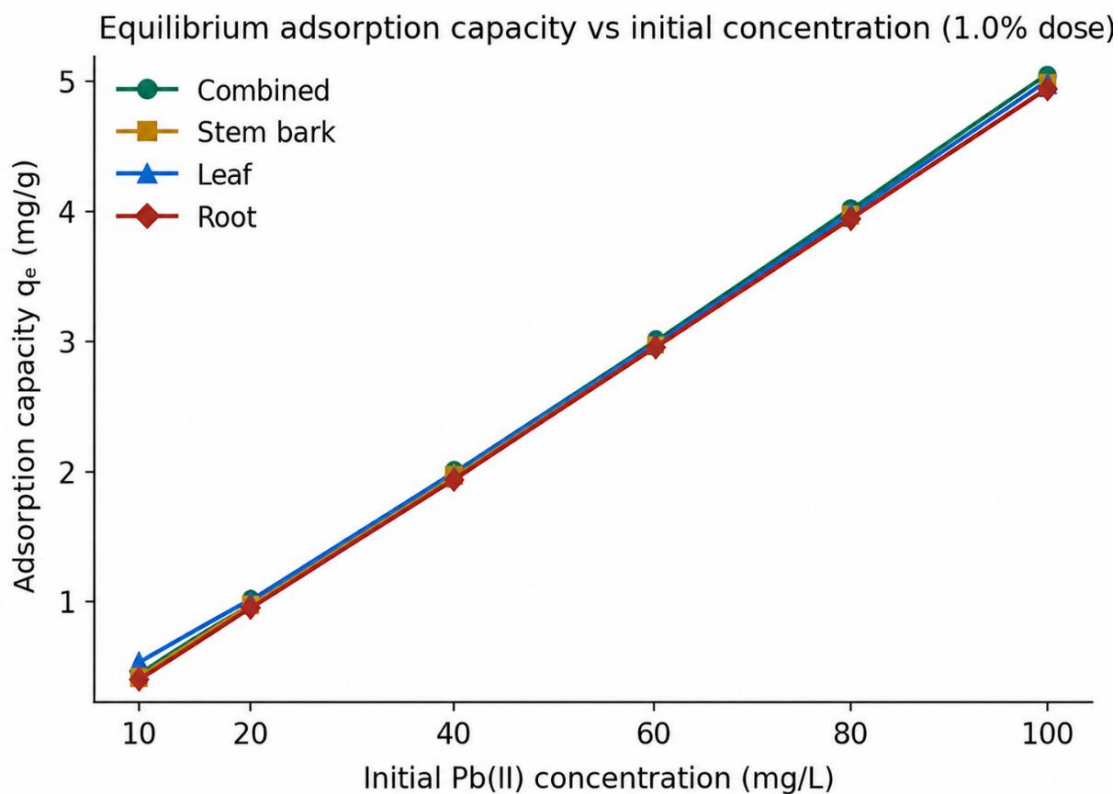


Figure 4: Effect of initial Pb(II) concentration on equilibrium adsorption capacity, q_e (1.00% dose, 3 h).

Effect of Biosorbent Dose

The removal efficiency only slightly increased (from 99.81% to 99.97% for the overall biosorbent) when the biosorbent dose was increased from 0.25% to 1.00%; similar patterns were seen for the individual plant sections (Figure 5). As observed for *A. leiocarpus* stem bark by Adeyemi et al. (2021) and alginate-encapsulated rice husk ash by Khader et al. (2023), this diminishing dose-response is consistent with a dosage threshold beyond which further biosorbent produces limited further benefit. For the isotherm and kinetic analyses that followed, the 1.00% dose was kept as the reference condition.

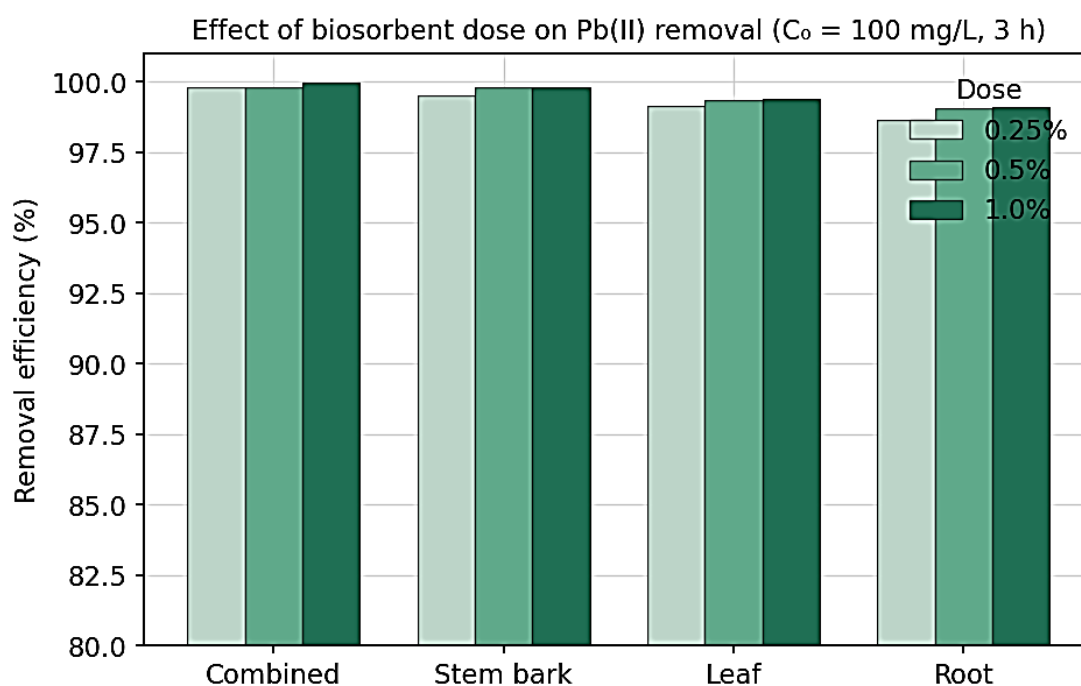


Figure 5: Effect of biosorbent dose on Pb(II) removal efficiency ($C_0 = 100$ mg/L, 3 h).

Effect of Biosorbent Type and Control Experiments

The mixed biosorbent slightly outperformed stem bark, leaf, and root beads at the greatest equilibrium removal (99.97%) at the 1.00% dose and 100 mg/L starting concentration (Figure 6). According to the mechanistic interpretations of Adeyemi et al. (2021), Mohammed et al. (2022), and Nnaji et al. (2022) for individual *A. leiocarpus* tissues, this is consistent with the pooling of complementary functional groups—hydroxyl, carboxyl, and other oxygen-containing moieties—contributed by the three plant parts. The alginate-only control removed an intermediate fraction (~35.0%) due to the intrinsic ion

exchange of Ca^{2+} for Pb^{2+} within the alginate matrix, but the lead solution without any beads (no-adsorbent blank) exhibited very little removal ($\sim 2.9\%$) (Russo et al., 2024; Ablouh et al., 2019). Importantly, removal by the whole biosorbents ($>99\%$) was significantly higher than that of the alginate matrix alone, indicating that the immobilized plant biomass is the main source of lead uptake.

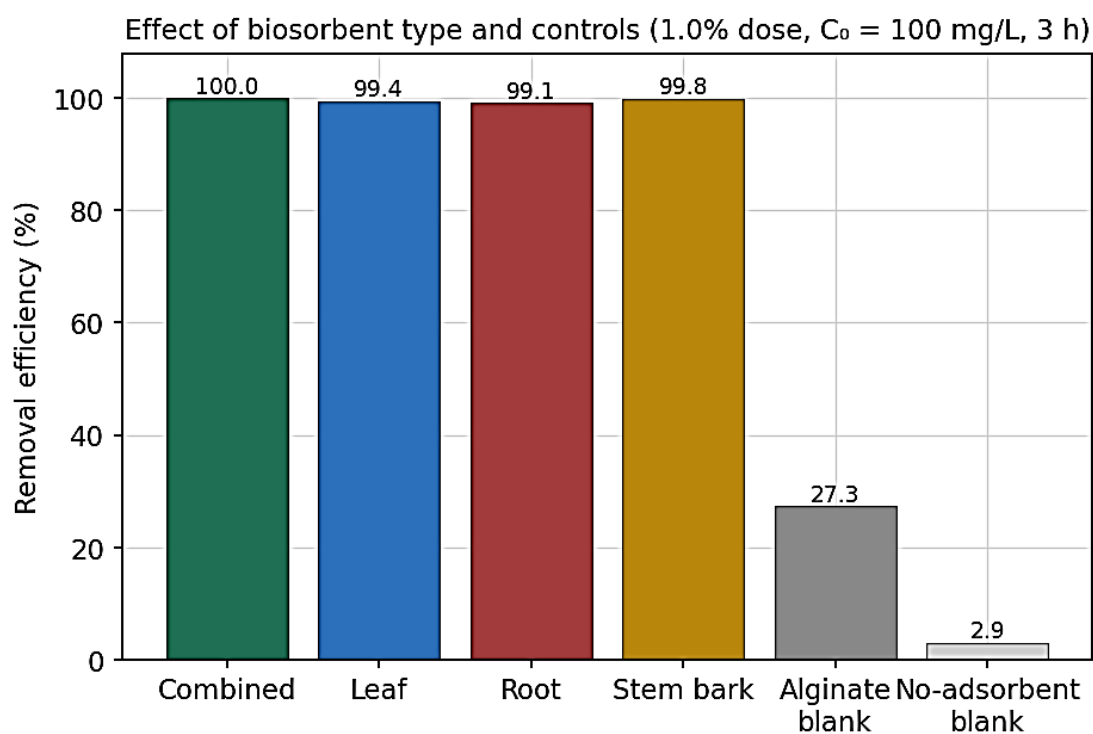


Figure 6: Comparison of Pb(II) removal efficiency among the four biosorbent types and the two controls (1.00% dose, $C_0 = 100 \text{ mg/L}$, 3 h).

Adsorption Isotherm Studies

Because of the extremely high removal efficiencies obtained, which kept equilibrium concentrations low and prevented the system from approaching the monolayer saturation plateau on which the Langmuir model is based, the equilibrium data were poorly described by the Langmuir model, with low and inconsistent R^2 values and physically implausible (negative) parameters for several biosorbents (Figure 7). With R^2 values of 0.801, 0.807, 0.806, and 0.9999 for the combined stem bark, leaf, and root biosorbents, respectively, the Freundlich model, on the other hand, offered a significantly better fit (Figure 8), suggesting that lead biosorption takes place on an energetically heterogeneous surface consistent with the chemical complexity of the calcium-alginate matrix combined

with lignocellulosic plant biomass. Although Adetoro and Ojoawo (2020) reported Langmuir dominance for unmodified stem bark powder, this result is consistent with the Freundlich-model dominance ($R^2 = 0.961$) reported for carbonized *A. leiocarpus* leaf biomass by Ibrahim et al. (2019). This suggests that alginate encapsulation introduces additional surface heterogeneity relative to raw biomass.

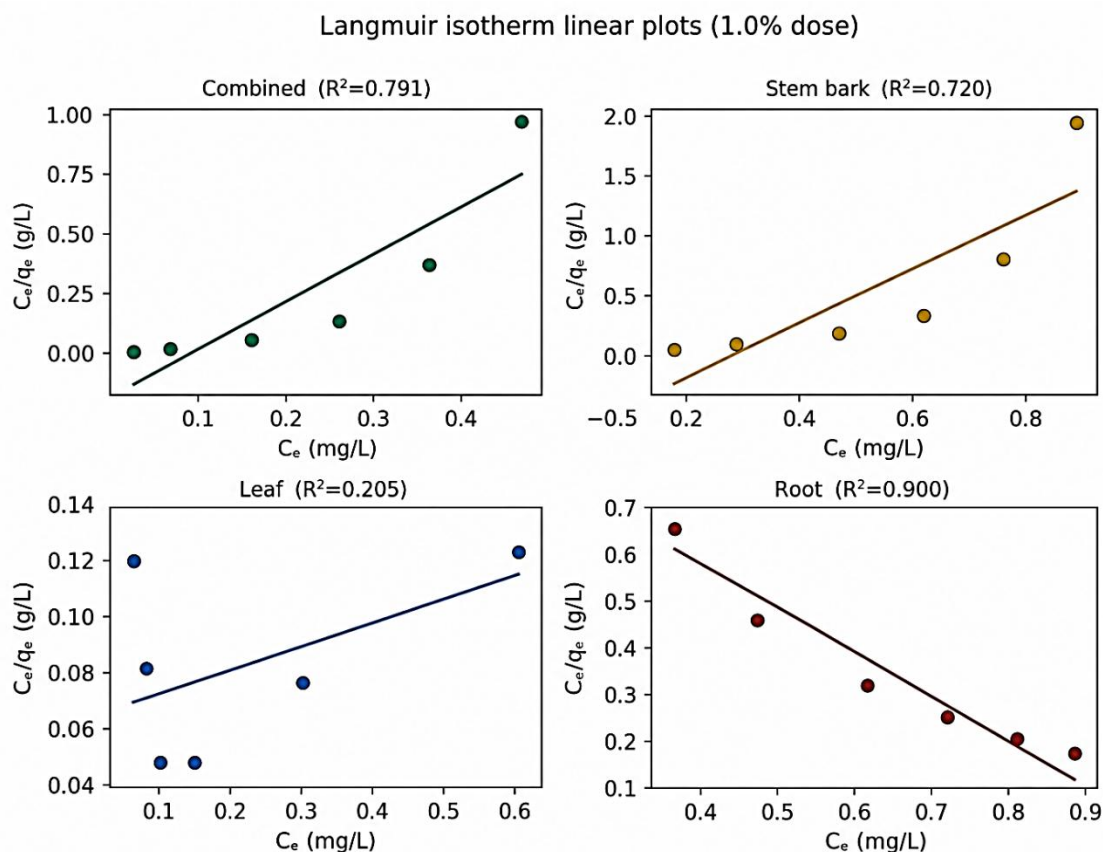


Figure 7: Langmuir isotherm linear plots (C_e/q_e vs C_e) for the four biosorbents (1.00% dose).

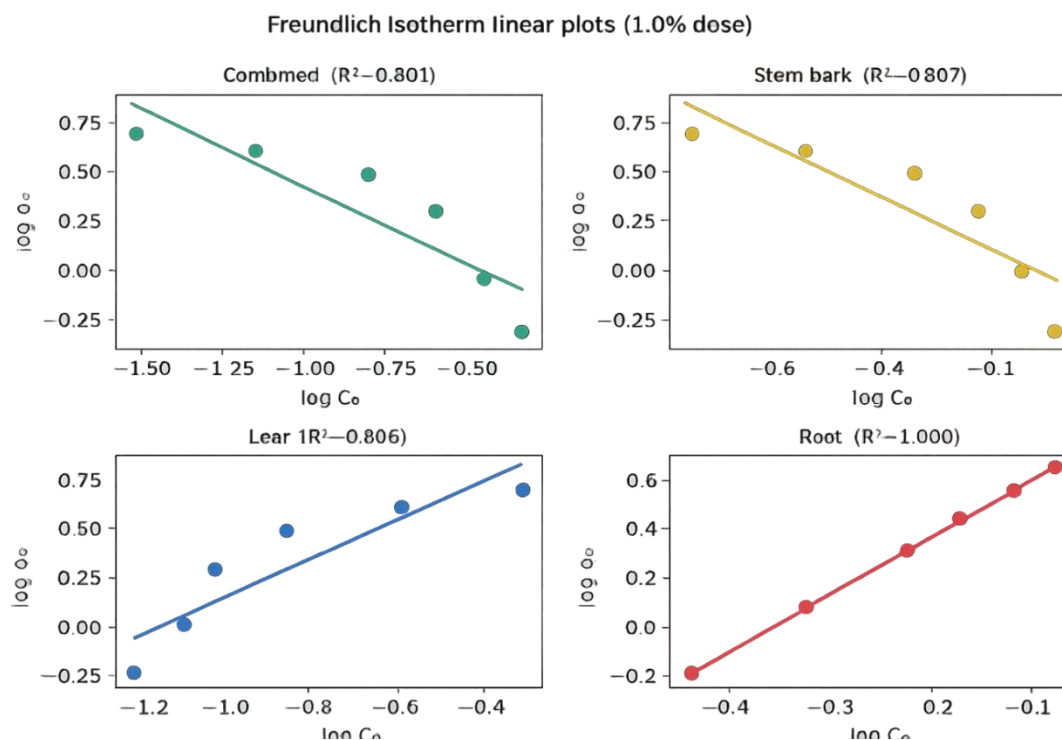


Figure 8: Freundlich isotherm linear plots ($\log q_e$ vs $\log C_e$) for the four biosorbents (1.00% dose).

Adsorption Kinetics

The calculated equilibrium capacities were significantly lower than the experimental values (for instance, 0.251 mg/g calculated versus 4.998 mg/g experimental for the combined biosorbent), suggesting that the pseudo-first-order model does not accurately represent the biosorption process over the entire contact period, even though it produced reasonably high correlation coefficients (Figure 9).

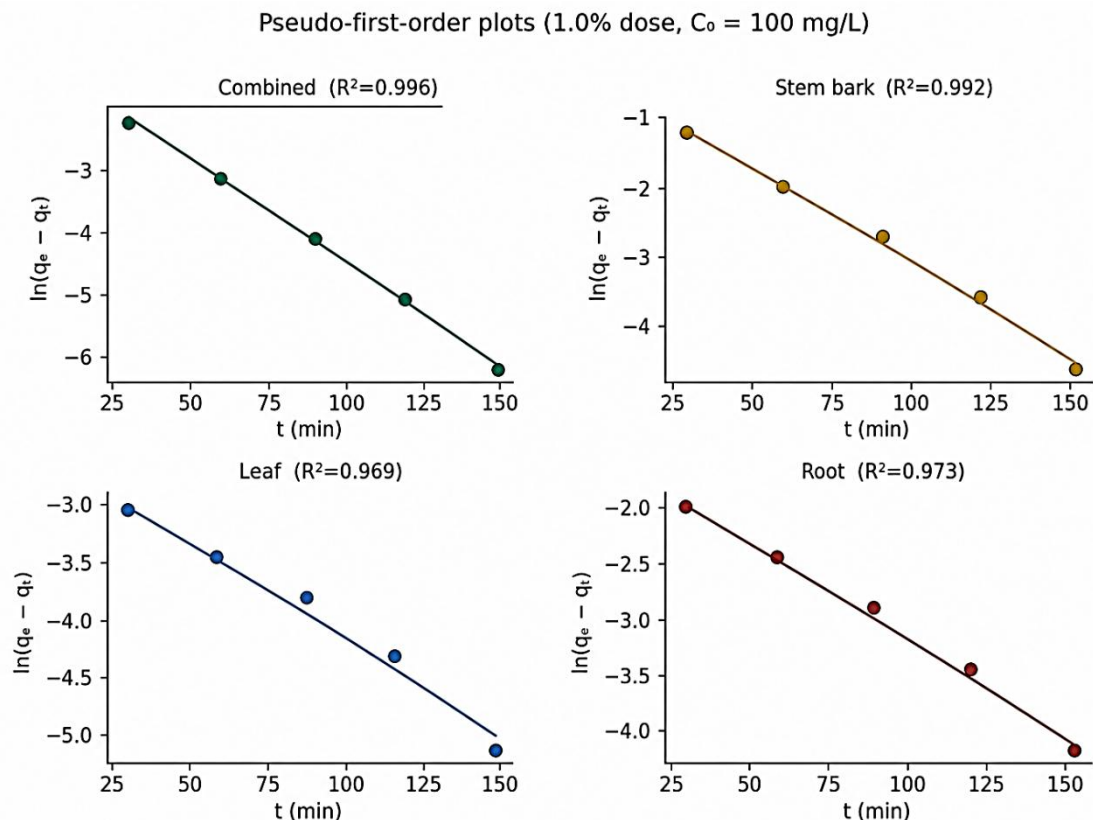


Figure 9: Pseudo-first-order kinetic plots for the four biosorbents (1.00% dose, $C_0 = 100$ mg/L).

In contrast, the pseudo-second-order model provided an excellent fit for all four biosorbents ($R^2 = 1.000$), with calculated equilibrium capacities (5.018, 5.061, 4.979, and 4.984 mg/g for combined, stem bark, leaf, and root, respectively) closely matching experimental values (4.998, 4.991, 4.970, and 4.955 mg/g) (Figure 10). This strongly suggests that chemisorption is the mechanism that controls the rate. This is in line with pseudo-second-order kinetics described for chitosan-alginate hybrid beads by Ablouh et al. (2019) and for other *A. leiocarpus*-based biosorbents by Yakubu et al. (2018), Mohammed et al. (2022), and Adeyemi et al. (2021).

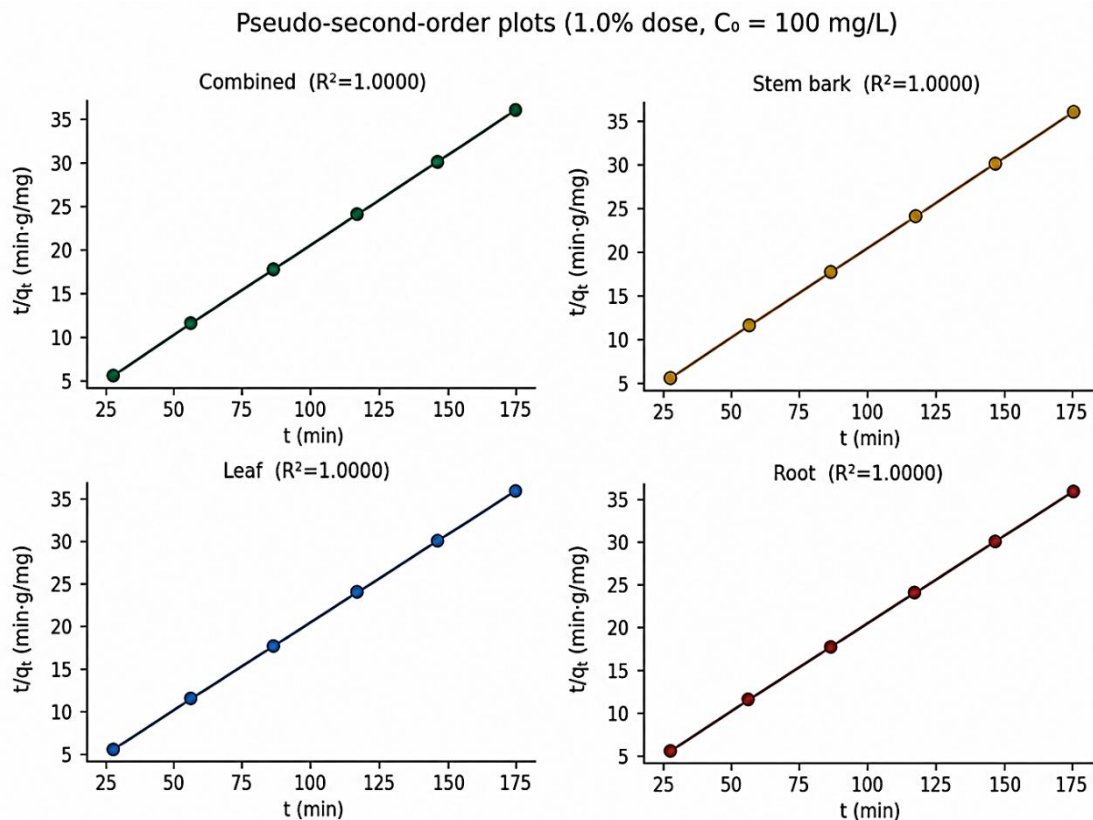


Figure 10: Pseudo-second-order kinetic plots for the four biosorbents (1.00% dose, $C_0 = 100$ mg/L).

Although intraparticle-diffusion plots were linear, they displayed significant positive intercepts ($C = 4.54\text{--}4.90$ mg/g), suggesting that boundary-layer (film) diffusion was not the only rate-controlling step but also contributed to the adsorption rate (Figure 11). This multi-mechanism behavior complements the dominant chemisorptive mechanism found by the pseudo-second-order analysis and is consistent with the findings of Russo et al. (2024) and Khader et al. (2023) for other alginate-encapsulated composite beads. Lead ions must first pass through an external film before diffusing into the alginate matrix and reaching the plant-biomass binding sites.

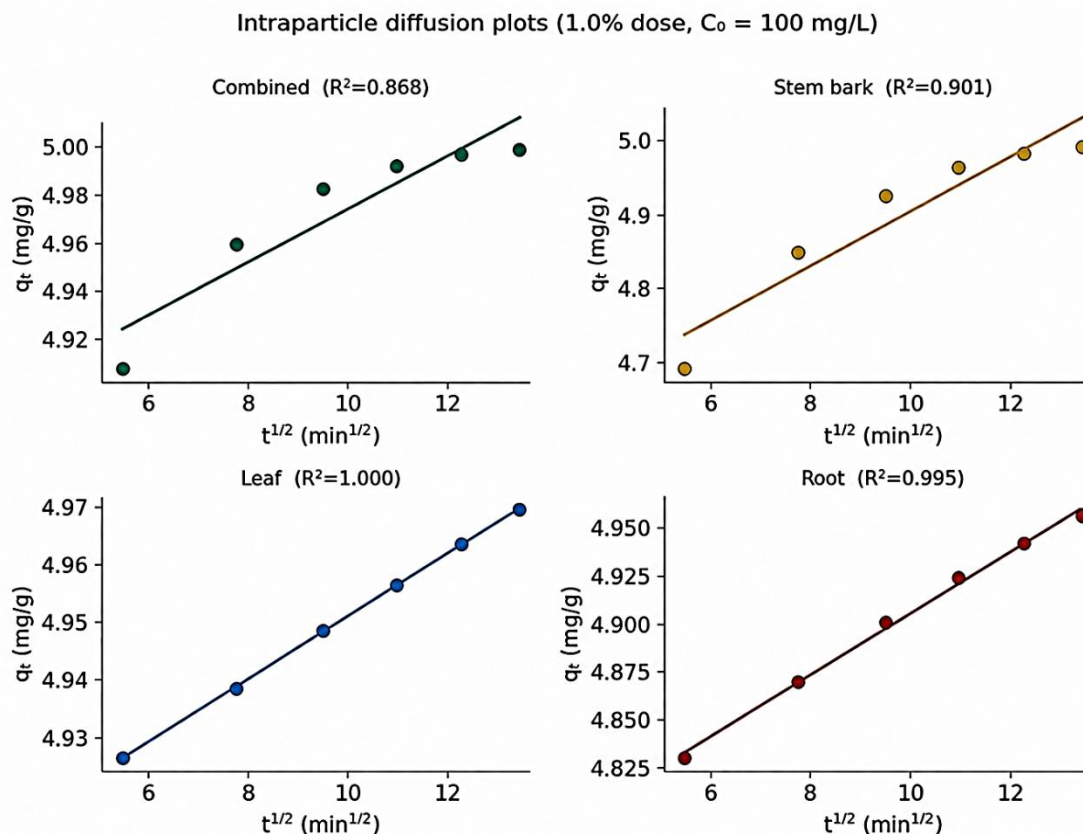


Figure 11: Intraparticle-diffusion plots (q_t vs $t^{0.5}$) for the four biosorbents (1.00% dose, $C_0 = 100$ mg/L).

CONCLUSION

Mechanically stable and highly effective biosorbents for the removal of Pb(II) from aqueous solution were created by immobilizing powdered *Anogeissus leiocarpus* biomass in calcium alginate. The combined stem, leaf, and root biosorbent achieved the highest equilibrium removal (99.97%) at an optimal dose of 1.00% and initial lead concentration of 100 mg/L. While kinetic data closely matched the pseudo-second-order model, indicating chemisorption as the predominant rate-controlling mechanism, complemented by boundary-layer diffusion, equilibrium behavior was best described by the Freundlich isotherm, indicating adsorption onto a heterogeneous surface. These results show that sodium-alginate-immobilized *A. leiocarpus* biomass is a viable, affordable, and sustainable biosorbent for lead-contaminated water. They also encourage more research into its performance under continuous flow conditions, its potential for regeneration and reuse, and its promotion as an accessible remediation option in settings with limited resources.

REFERENCES

- Abdelhafez, A. A., Li, J., & Abbas, M. H. H. (2021). Feasibility of using natural materials for the removal of heavy metals from aqueous solutions: Batch adsorption and isotherm studies. *Environmental Technology and Innovation*, 21, Article 101230.
- Ablouh, E.-H., Hanani, Z., Eladlani, N., Rhazi, M., & Taourirte, M. (2019). Chitosan microspheres/sodium alginate hybrid beads: An efficient green adsorbent for heavy metals removal from aqueous solutions. *Sustainable Environment Research*, 29, Article 5. <https://doi.org/10.1186/s42834-019-0004-9>
- Adekola, F. A., & Ogunleye, O. A. (2023). Activated biochar from *Anogeissus leiocarpus* leaves for efficient removal of heavy metals in aqueous systems. *Environmental Technology and Innovation*, 32, Article 103072.
- Adetoro, E. A., & Ojoawo, S. O. (2020). Optimization study of biosorption of toxic metals from mining wastewater using *Azadirachta indica* bark adsorbents. *Water Science and Technology*, 82(5), 887–904. <https://doi.org/10.2166/wst.2020.394>
- Adeyemi, O. S., Akinmoladun, F. O., & Abiola, O. J. (2021). Cadmium biosorption using stem bark of *Anogeissus leiocarpus*: Kinetic, equilibrium, and thermodynamic studies. *Environmental Technology and Innovation*, 22, Article 101438.
- Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, 2019(1), Article 6730305. <https://doi.org/10.1155/2019/6730305>
- Bustos Terrones, Y. D., et al. (2024). Sodium alginate immobilization of plant biomass for enhanced pollutant biosorption: A review. *Journal of Environmental Chemical Engineering*, 12(1), Article 111234.
- Ibrahim, M. B., Sani, A., & Yaro, A. H. (2019). Adsorption of lead ions onto carbonized *Anogeissus leiocarpus* leaf biomass: Isotherm and kinetic studies. *Journal of Environmental Chemical Engineering*, 7(4), Article 103208.
- Ibrahim, M. B., Sani, A., & Yaro, A. H. (2022). Biosorption of heavy metals using unmodified *Anogeissus leiocarpus* leaf biomass. *Water, Air, and Soil Pollution*, 233, Article 112.
- Khader, E. H., Muslim, S. A., & Al-Ani, F. H. (2023). Rice husk ash-alginate composite beads for heavy metal removal from aqueous solution. *Journal of Water Process Engineering*, 51, Article 103456.
- Mohammed, A., Sani, I., & Yakubu, M. (2022). Acid-activated *Anogeissus leiocarpus* root biomass for Pb^{2+} and Ni^{2+} removal: Isotherm and kinetic studies. *Journal of Environmental Management*, 305, Article 114362.
- Musa, M. A., & Yakubu, M. (2021). Citric acid-modified *Anogeissus leiocarpus* leaf biomass for lead biosorption from aqueous solution. *Journal of Chemical Technology and Biotechnology*, 96(7), 1832–1841.
- Nnaji, N. D., Onyeaka, H., Miri, T., & Ugwa, C. (2023). Bioaccumulation for heavy metal removal: A review. *SN Applied Sciences*, 5(5), Article 125. <https://doi.org/10.1007/s42452-023-05351-6>

- Russo, T., Fucile, P., Giacometti, R., & Sannino, F. (2024). Magnetic alginate-based composite beads for heavy metal remediation of contaminated water. *Polymers*, 16(2), Article 210.
- Sanders, A. P., Claus Henn, B., & Wright, R. O. (2015). Perinatal and childhood exposure to cadmium, manganese, and metal mixtures and effects on cognition and behavior: A review of recent literature. *Current Environmental Health Reports*, 2(3), 284–294. <https://doi.org/10.1007/s40572-015-0058-8>
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In A. Luch (Ed.), *Molecular, clinical and environmental toxicology: Volume 3: Environmental toxicology* (pp. 133–164). Springer. https://doi.org/10.1007/978-3-7643-8340-4_6
- Wang, T., Xu, H., Zhang, Y., & Li, M. (2022). Neurodevelopmental toxicity of lead and cadmium: An update and perspectives. *Frontiers in Toxicology*, 4, Article 879632.
- Yakubu, M., Musa, M. A., & Aliero, A. A. (2018). Kinetics and equilibrium studies of heavy metal biosorption on raw *Anogeissus leiocarpus* root powder. *African Journal of Environmental Science and Technology*, 12(6), 214–222.