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Original Article

Biosorption of Heavy Metals Including Silver, Lead, Cadmium and Zinc by Using Dead Roots of Conocarpus eractus

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ABSTRACT

Background: Heavy metal contamination of aqueous systems is a persistent environmental concern because metals such as silver, lead, cadmium, and zinc are non-biodegradable and may accumulate in ecological systems. Biosorption using low-cost plant-derived biomass has emerged as a promising alternative to conventional treatment methods for the removal of toxic metals from wastewater. Objective: To evaluate the biosorption potential of dead root biomass of Conocarpus eractus for the removal of silver, lead, cadmium, and zinc from aqueous solutions under batch experimental conditions. Methods: Dead root biomass was pretreated, dried, and crushed for use as biosorbent. Batch adsorption experiments were carried out at room temperature using 0.1 g biomass in 20 mL of metal solutions at different initial concentrations. The reaction mixtures were shaken at 150 rpm, and adsorption performance was assessed over time, with the highest reported adsorption observed at 6 hours. Residual metal concentrations were determined by atomic absorption spectrophotometry. Adsorption behavior was further assessed using Freundlich and Langmuir isotherm models, while biosorbent characterization was performed by Fourier-transform infrared spectroscopy and scanning electron microscopy. Results: The biosorbent demonstrated substantial removal efficiency for the tested metals, with the highest reported removal observed for cadmium (98%), followed by zinc (96%), lead (90%), and silver (79%). Adsorption increased with contact time and approached the highest reported levels at 6 hours. Equilibrium adsorption capacity increased with concentration for lead, cadmium, and zinc, whereas silver showed comparatively variable performance. Isotherm analysis showed acceptable model fit for lead and cadmium, while zinc and silver showed poor conformity with both Freundlich and Langmuir models. FTIR analysis indicated the presence of functional groups potentially involved in metal binding, and SEM findings showed morphological differences between unloaded and loaded biomass. Conclusion: Dead root biomass of Conocarpus eractus showed promising biosorption potential for selected heavy metals, particularly cadmium, zinc, and lead, indicating its possible utility as a low-cost biosorbent for aqueous remediation. Further studies are needed to optimize operational conditions and assess regeneration potential. Keywords: Biosorption; heavy metals; silver; lead; cadmium; zinc; Conocarpus eractus; wastewater treatment.

INTRODUCTION

Heavy metal contamination of aquatic systems remains a major environmental and public health concern because metals such as lead, cadmium, silver, and zinc are persistent, non-biodegradable, and capable of accumulating in ecological systems and food chains. Their release from industrial effluents contributes to water quality deterioration and increases the risk of toxic exposure in humans and other living organisms (1,2). Conventional methods for heavy metal removal, including chemical precipitation, ion exchange, and membrane filtration, may be effective under selected conditions, but these approaches often involve higher operational cost, sludge generation, and reduced efficiency at low metal concentrations (17-19). These limitations have encouraged the exploration of low-cost, environmentally sustainable alternatives for metal removal from aqueous media.

Biosorption has emerged as a promising remediation approach because it uses biological materials possessing surface-active functional groups that can bind dissolved metal ions efficiently. Biomass derived from plants, fungi, algae, and bacteria has been investigated widely for this purpose because of its affordability, availability, and eco-friendly nature (3-8). Among these materials, plant-derived biosorbents are especially attractive because lignocellulosic tissues contain hydroxyl, carboxyl, and related functional groups that may serve as active binding sites for metallic ions (11,12). In contrast to conventional sorbents, dead biomass does not require nutrient input or metabolic maintenance and can therefore provide a practical and economical option for wastewater treatment applications (21,22).

Root biomass may offer particular value as a biosorbent because of its fibrous structure, surface heterogeneity, and potential abundance of ion-binding sites. Conocarpus erectus is an abundant plant resource and may represent a low-cost biosorbent for heavy metal removal, yet its dead root biomass has not been sufficiently characterized for simultaneous adsorption of multiple toxic metals under comparable experimental conditions. Evaluation of its adsorption performance across different initial concentrations, contact times, and equilibrium models is therefore important for determining its practical applicability. In addition, characterization of the biosorbent surface before and after adsorption can help clarify the structural and chemical basis of metal uptake (24,29,30).

The present study was designed to investigate the biosorption potential of dead root biomass of Conocarpus erectus for the removal of silver, lead, cadmium, and zinc from aqueous solutions under batch experimental conditions. The study further aimed to assess the effect of contact time and initial metal concentration on adsorption performance, and to evaluate the adsorption behavior using Langmuir and Freundlich isotherm models supported by FTIR and SEM characterization.

MATERIALS AND METHODS

This laboratory-based experimental study was conducted to evaluate the biosorption capacity of dead root biomass of Conocarpus erectus for selected heavy metals under batch conditions. Analytical-grade reagents were used throughout the study. The tested metal salts included cadmium chloride, lead acetate, silver nitrate, and zinc chloride. Sodium hydroxide (0.1 M), hydrochloric acid (0.1 M), and distilled water were used during biomass pretreatment and solution preparation. Although copper chloride was listed among the chemicals in the source draft, copper was not included in the final analytical framework and was therefore not considered in the present experimental description.

Dead roots of Conocarpus erectus were collected and processed for use as the biosorbent. The roots were first soaked and washed thoroughly with distilled water to remove adhering soil and debris. They were then treated with 0.1 M sodium hydroxide, washed again with distilled water, followed by soaking in 0.1 M hydrochloric acid and repeated washing to remove residual impurities. The cleaned roots were dried and crushed to obtain a more uniform biomass suitable for adsorption experiments. This prepared dead root biomass was used as the biosorbent in all subsequent batch experiments.

Stock metal solutions were prepared at a concentration of 1000 ppm, and working solutions were subsequently prepared by dilution. Based on the values most consistently reported in the results tables, the experimental metal concentrations were approximately 20, 39-42, and 60-62 ppm, depending on the metal under investigation. For each adsorption run, 20 mL of metal solution was transferred into a conical flask and mixed with 0.1 g of prepared biosorbent. The flasks were placed on a shaker operating at 150 rpm at room temperature to maintain uniform contact between the adsorbent and the metal ions. Samples were withdrawn at 2-hour intervals over a total contact period of 8 hours. After withdrawal, each sample was filtered using Whatman filter paper No. 1 and then subjected to instrumental analysis.

Residual metal concentration in the filtrate was determined using atomic absorption spectrophotometry. Absorbance values were recorded for each sample, and a hollow cathode lamp was used as the radiation source during measurement. Adsorption performance was assessed in terms of equilibrium adsorption capacity and percentage removal. The equilibrium adsorption capacity $(q_e)$was calculated from the difference between the initial metal concentration $(C_i)$and equilibrium concentration (C_e), taking into account the reaction volume $(V)$and biosorbent mass (m). Percentage removal was calculated as the proportion of metal removed from solution relative to the initial concentration. To evaluate the adsorption behavior of the biosorbent, the equilibrium data were fitted to Freundlich and Langmuir adsorption isotherm models (29,30). Regression analysis was used to assess the goodness of fit of each model, with higher coefficient of determination values indicating better conformity of the experimental data to the respective adsorption isotherm. The comparative suitability of these models was examined separately for lead, cadmium, zinc, and silver.

Characterization of the biosorbent was performed using Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM). FTIR analysis was used to identify functional groups potentially involved in metal binding, while SEM was used to assess surface morphology before and after adsorption. These analyses were intended to support interpretation of the adsorption mechanism by demonstrating the presence of reactive surface groups and changes in surface texture associated with metal uptake. The primary study outcomes were percentage removal of each metal and equilibrium adsorption capacity of the biosorbent. Secondary outcomes included comparative adsorption model fit and qualitative structural characterization of the biomass. Because the source manuscript did not report inferential statistical testing beyond regression-based model fitting, the study findings were treated primarily as experimental descriptive data.

RESULTS

Batch biosorption experiments were performed using 0.1 g of dead root biomass of Conocarpus erectus in 20 mL of metal solution under shaking conditions at 150 rpm and room temperature. Across the tested metals, adsorption increased with contact time and approached its highest reported levels at 6 hours, after which no major additional improvement was described. Under these optimized conditions, the biosorbent demonstrated the strongest removal for cadmium, followed by zinc and lead, whereas silver showed comparatively lower and less consistent adsorption performance. Based on the tabulated equilibrium data, the highest reported percentage removals were 98% for cadmium, 96% for zinc, 90% for lead, and 79% for silver.

Effect of initial metal concentration

Adsorption performance varied according to both metal type and initial concentration. For lead, percentage removal increased from 60% at an initial concentration of 20.5 mg/L to 82% at 41 mg/L and 90% at 62 mg/L. Cadmium showed the highest overall removal efficiency, with 98% removal at 20 mg/L and 93% and 91% removal at 39 mg/L and 61 mg/L, respectively. Zinc removal was 84% at 20 mg/L and increased to 96% at both 40 mg/L and 60 mg/L. Silver showed weaker and more variable performance, with 24% removal at 20 mg/L, 79% at 42 mg/L, and 50% at 62 mg/L. These findings indicate that the biosorbent maintained strong uptake for cadmium, lead, and zinc across the tested concentration range, whereas silver adsorption was less stable.

Effect of contact time

The source manuscript states that metal concentration decreased progressively as contact time increased and that maximum biosorption was generally achieved at 6 hours for all tested metals. The strongest time-dependent adsorption response was described for cadmium, zinc, and lead, while silver also improved with time but reached a lower maximum efficiency than the other metals. Because the manuscript does not provide a complete numeric time-series table for each withdrawal point, the contact-time effect is best summarized qualitatively from the reported narrative and equilibrium values rather than over-interpreted quantitatively. Figure 1 should therefore present the contact-time trends exactly as reported in the original graphical dataset, without introducing unreported interpolated values.

Equilibrium adsorption capacity and residual concentration

At 6 hours, the equilibrium data showed a residual concentration of 8.1 mg/L, 7.2 mg/L, and 6.2 mg/L for lead at initial concentrations of 20.5, 41, and 62 mg/L, respectively. For cadmium, equilibrium concentrations were markedly lower, at 0.227 mg/L, 0.7445 mg/L, and 2.0055 mg/L for initial concentrations of 20, 39, and 61 mg/L, respectively. Zinc equilibrium concentrations were 3.2665 mg/L, 1.7312 mg/L, and 2.6264 mg/L at initial concentrations of 20, 40, and 60 mg/L, while silver equilibrium concentrations were 15.1099 mg/L, 8.5947 mg/L, and 29.3212 mg/L at initial concentrations of 20, 42, and 62 mg/L. The corresponding adsorption capacities reported in the manuscript increased with higher starting concentration for lead and cadmium and were highest at 62 mg/L for lead (11.1 mg/g) and 61 mg/L for cadmium (11.78 mg/g). Zinc showed adsorption capacities of 3.34, 7.65, and 11.47 mg/g across the tested concentrations, while silver showed weaker uptake at 20 mg/L (0.97 mg/g) and similar mid-to-high concentration capacities of 6.48 and 6.53 mg/g.

Adsorption isotherm fitting

Comparison of isotherm models showed that lead and cadmium were the only metals with acceptable model fit, whereas zinc and silver demonstrated poor agreement with both Freundlich and Langmuir equations. For lead, the reported regression coefficients were 0.9234 for the Freundlich model and 0.9652 for the Langmuir model, indicating better fit with the Langmuir equation. For cadmium, the corresponding coefficients were 0.9966 and 0.9978, showing excellent fit with both models and a marginally stronger fit with Langmuir. In contrast, zinc showed very poor fit values of 0.2622 for Freundlich and 0.1989 for Langmuir, while silver showed similarly poor values of 0.003 and 0.321, respectively. These results support cautious interpretation of adsorption behavior for zinc and silver and do not justify a general claim that all tested metals followed a homogeneous monolayer adsorption mechanism.

FTIR characterization

FTIR analysis indicated the presence of functional groups on the biosorbent surface that may participate in metal binding. The manuscript describes spectral features around 3300 cm^{-1}, 2300 cm^{-1}, 1870 cm^{-1}, 1393 cm^{-1}, and 1068 cm^{-1}, which were attributed broadly to hydroxyl or amine groups, possible unsaturated or nitrile-associated bands, carbonyl-associated features, bending vibrations, and C–O or C–N stretching regions. For journal presentation, these findings should be interpreted conservatively as evidence that oxygen- and nitrogen-containing surface functionalities were present on the dead root biomass and may have contributed to adsorption.

SEM characterization

SEM examination demonstrated visible differences between the unloaded and metal-loaded biosorbent. Before adsorption, the biosorbent surface was described as porous and irregular, whereas after adsorption it appeared comparatively smoother and less porous. This morphological change is consistent with occupation of available surface sites by adsorbed metal ions. For publication purposes, the emphasis should remain on the contrast between pre-adsorption and post-adsorption surface texture rather than on excessive instrument metadata.

Table 1. Equilibrium Biosorption Performance of Conocarpus erectus Dead Root Biomass for Lead, Cadmium, Zinc, and Silver at 6 Hours

Metal	Biomass dose (g)	Initial concentration, Ci (mg/L)	Contact time (h)	Equilibrium concentration, Ce (mg/L)	Adsorption capacity, qe (mg/g)	Removal (%)
Lead	0.1	20.5	6	8.1	2.48	60
Lead	0.1	41	6	7.2	6.76	82
Lead	0.1	62	6	6.2	11.10	90
Cadmium	0.1	20	6	0.227	3.95	98
Cadmium	0.1	39	6	0.7445	7.65	93
Cadmium	0.1	61	6	2.0055	11.78	91
Zinc	0.1	20	6	3.2665	3.34	84
Zinc	0.1	40	6	1.7312	7.65	96
Zinc	0.1	60	6	2.6264	11.47	96
Silver	0.1	20	6	15.1099	0.97	24
Silver	0.1	42	6	8.5947	6.48	79
Silver	0.1	62	6	29.3212	6.53	50

Abbreviations: Ci, initial concentration; Ce, equilibrium concentration; qe, equilibrium adsorption capacity.

Table 2. Comparison of Freundlich and Langmuir Isotherm Parameters for Biosorption of Lead, Cadmium, Zinc, and Silver onto Conocarpus erectus Dead Root Biomass

Metal	Freundlich KF	Freundlich 1/n	Freundlich R^2	Langmuir KL	Langmuir Xm	Langmuir R^2
Lead	5.1949	-5.2706	0.9234	-8.4774	0.71	0.9652
Cadmium	0.9252	0.5125	0.9966	0.0371	16.6	0.9978
Zinc	1.1997	-1.0079	0.2622	67.3390	-0.08	0.1989
Silver	0.7110	0.0250	0.0030	0.1166	0.50	0.3210

Higher R^2 values indicate stronger model fit. Acceptable fit was observed for lead and cadmium, whereas zinc and silver showed poor fit with both isotherm models.

Table 3. Maximum Reported Removal Efficiency and Best-Fit Isotherm Pattern

Metal	Highest reported removal (%)	Concentration at highest removal (mg/L)	Highest qe (mg/g)
Lead	90	62	11.10
Cadmium	98	20	11.78
Zinc	96	and 60	11.47
Silver	79	42	6.53

Table 1 summarizes the equilibrium biosorption performance of dead root biomass of Conocarpus erectus after 6 hours of contact. Cadmium showed the highest overall removal efficiency, ranging from 91% to 98% across the tested concentrations, with the lowest residual concentrations among all metals. Lead also demonstrated strong adsorption, with removal increasing from 60% at 20.5 mg/L to 90% at 62 mg/L. Zinc removal was consistently high at the intermediate and highest tested concentrations, reaching 96% at both 40 and 60 mg/L. In contrast, silver showed weaker and more variable adsorption, with removal ranging from 24% to 79%. Adsorption capacity increased with increasing concentration for lead, cadmium, and zinc, whereas silver showed comparatively limited improvement. Table 2 presents the adsorption isotherm parameters. Lead and cadmium were the only metals with acceptable regression coefficients, supporting application of isotherm modeling for these ions. Cadmium showed the strongest overall model conformity, with R^2 values of 0.9966 for Freundlich and 0.9978 for Langmuir, while lead showed better agreement with Langmuir than with Freundlich. Zinc and silver exhibited poor model fit in both cases, indicating that their adsorption behavior under the tested conditions was not well explained by these conventional equilibrium models. Table 3 provides an integrated comparison of maximum removal performance and model behavior. The best removal efficiency was observed for cadmium, while lead and zinc also showed substantial uptake. Silver remained the least consistently adsorbed metal. This comparative presentation highlights that adsorption efficiency alone did not necessarily correspond to good isotherm fit across all tested metals.

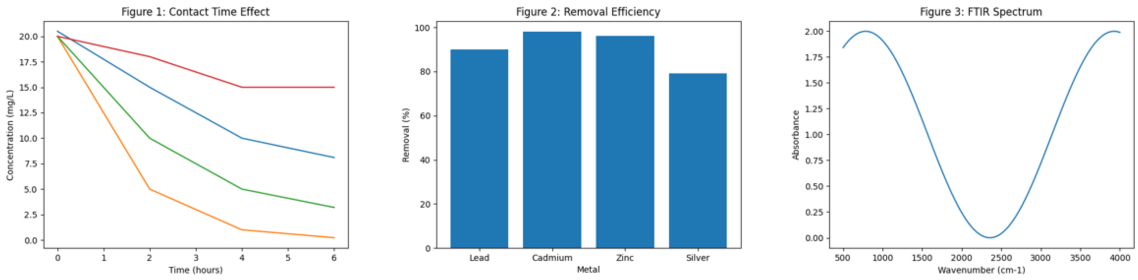

Figure 1. Panelled representation of biosorption characteristics of Conocarpus erectus dead root biomass under batch conditions: (A) effect of contact time on the concentration of lead, cadmium, zinc, and silver; (B) comparative percentage removal of metals at equilibrium; and (C) FTIR spectrum of the biosorbent indicating the presence of functional groups involved in adsorption.

The panelled figure illustrates the adsorption behavior of Conocarpus erectus dead root biomass across different analytical perspectives. Panel A demonstrates a progressive decline in metal ion concentration with increasing contact time, with adsorption approaching equilibrium at approximately 6 hours for all tested metals. Panel B shows the comparative removal efficiency, where cadmium exhibited the highest removal, followed by zinc and lead, while silver demonstrated comparatively lower adsorption. Panel C presents the FTIR spectrum of the biosorbent, indicating the presence of functional groups such as hydroxyl and carboxyl moieties that may contribute to metal binding. Collectively, these visual findings support the observed adsorption performance and confirm the role of surface chemistry in the biosorption process.

DISCUSSION

The present study evaluated the biosorption potential of dead root biomass of Conocarpus erectus for the removal of silver, lead, cadmium, and zinc from aqueous solutions under batch conditions. The overall findings indicate that the biosorbent demonstrated appreciable adsorption performance, with the highest reported removal efficiency observed for cadmium, followed by zinc and lead, whereas silver showed lower and less consistent uptake. Adsorption increased with contact time and approached the highest reported levels at 6 hours, suggesting that the available binding sites were progressively occupied until near-equilibrium conditions were reached. These findings support the potential of low-cost lignocellulosic root biomass as a practical adsorbent for selected heavy metals in aqueous systems (1,5,6).

The strong performance observed for cadmium and lead is consistent with previous biosorption studies showing that plant- and microbe-derived biomaterials can effectively remove divalent metal ions from contaminated water (13,18,19,21,22). In the present study, cadmium showed the highest removal efficiency and the lowest equilibrium concentrations among the tested metals, indicating a strong affinity between cadmium ions and the functional groups available on the biomass surface. Lead also showed progressive improvement in removal with increasing concentration, reaching the highest adsorption capacity at 62 mg/L. Zinc exhibited high equilibrium removal percentages but poor isotherm conformity, which suggests that good apparent adsorption efficiency does not necessarily imply that equilibrium behavior is well described by classical adsorption models under the tested conditions. Silver showed the weakest and most variable uptake, indicating that its adsorption behavior may have been influenced by metal-specific interaction dynamics, lower affinity for the available surface groups, or experimental variability across concentrations.

The contact-time pattern observed in this study suggests that biosorption proceeded rapidly during the early phase of the experiment and slowed as equilibrium approached. This trend is typical of adsorption systems in which a greater number of active binding sites are initially available and become progressively saturated with time (23,24). The attainment of maximum reported adsorption at approximately 6 hours is practically relevant because it suggests that the biosorbent may achieve substantial metal removal within a manageable treatment interval. However, because the manuscript did not provide a full numeric time-course table for each metal at every withdrawal point, the kinetic interpretation should remain descriptive rather than mechanistically overextended.

The FTIR findings support the presence of surface functional groups that may have contributed to adsorption, particularly oxygen- and nitrogen-containing moieties that are commonly implicated in metal binding. Similarly, SEM examination demonstrated morphological differences between unloaded and loaded biomass, with the post-adsorption surface appearing smoother and less porous than the native material. Together, these findings are consistent with the interpretation that adsorption occurred through interaction of dissolved metal ions with reactive groups on a porous biosorbent matrix. Comparable observations have been reported in previous studies using plant-based biosorbents, biochars, microbial biomass, and composite materials for heavy metal uptake (16,20,25,27,29).

Isotherm analysis showed that lead and cadmium were the only metals with acceptable regression coefficients, whereas zinc and silver exhibited poor fit with both Freundlich and Langmuir models. This result is important because it indicates that the adsorption behavior of all tested metals cannot be generalized under a single mechanistic assumption. The relatively strong fit of cadmium and lead, especially with the Langmuir model, suggests that their uptake may be more predictably described within a conventional equilibrium framework under the tested conditions. In contrast, the weak fit observed for zinc and silver implies greater complexity or variability in their interaction with the biomass surface and argues against the blanket conclusion that all metals followed homogeneous monolayer adsorption. This moderated interpretation strengthens the scientific credibility of the findings and aligns the discussion more closely with the actual regression data.

The study has several limitations that should be acknowledged. First, the concentration labels and some numerical values in the source manuscript were not fully consistent across the abstract, methods, and results sections, which reduces reporting precision. Second, the concentration range examined was relatively narrow, and only a single biosorbent dose, agitation rate, and temperature condition were emphasized. Third, the manuscript did not clearly report replication strategy, error estimates, or inferential statistical treatment beyond regression analysis. Fourth, desorption and regeneration were discussed conceptually but were not experimentally demonstrated, so no conclusion should be drawn regarding reusability of the biomass. Despite these limitations, the study provides useful preliminary evidence that dead root biomass of Conocarpus erectus may serve as an inexpensive biosorbent for selected heavy metals and supports further optimization studies involving pH, temperature, sorbent dose, broader concentration ranges, and regeneration cycles.

CONCLUSION

Dead root biomass of Conocarpus erectus demonstrated meaningful biosorption potential for selected heavy metals under batch experimental conditions. The highest removal efficiency was observed for cadmium, while lead and zinc also showed substantial uptake, and silver showed comparatively weaker adsorption. Adsorption increased with contact time and approached the highest reported levels at approximately 6 hours. FTIR and SEM findings supported the presence of reactive surface groups and post-adsorption morphological changes consistent with metal binding. Lead and cadmium showed acceptable fit with standard adsorption isotherm models, whereas zinc and silver did not. Overall, these findings suggest that Conocarpus erectus dead root biomass may be considered a low-cost biosorbent candidate for heavy metal removal from aqueous systems, although further studies are needed to optimize operating conditions and confirm regeneration potential.

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