Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2021.26761

215 (2021) 108–118
March

Elimination of cadmium(II) in aqueous solution using bamboo waste (*Bambusa vulgaris*)

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Received 7 May 2020; Accepted 5 November 2020

ABSTRACT

In this investigation, physically conditioned bamboo leaves (BL) were evaluated as an adsorbent in the removal of Cd(II) ions present in aqueous solution, determining the effect of pH, adsorbent dose, initial concentration, and temperature on the process. Experimental tests were carried out following a 2 K statistical experimental design. The biomass was characterized by scanning electron microscopy and energy-dispersive X-ray spectroscopy. It was established that BL has a rough, porous surface for use as a heavy metal adsorbent and that the adsorption process occurs by ion exchange. The adsorption kinetics indicated that it was fast for the first 15 min and equilibrium was reached after 25 min, and the pseudo-second-order model best described the process. The adsorption equilibrium was optimally adjusted to Langmuir and Freundlich's models, determining a maximum removal capacity of 103.09 mg g^{-1}. With regards to the thermodynamics, it was shown that the adsorption of Cd(II) on BL is endothermic, favorable, and spontaneous. From the results obtained, bamboo leaves are recommended for the adsorption of cadmium(II) present in the solution.

Keywords: Water treatment; Bioadsorption; Lignocellulosic residue; Physisorption

1. Introduction

Industrial and urban development, socio-economic factors, and the pollution of river systems by heavy metals such as Cd, Cr, Pb, Al, and Hg have become a serious global problem because these heavy metals possess high bioaccumulation capacity, toxicity, and resistance to biodegradability [1–3]. Among these, cadmium(Cd) is a contaminant that is not observed as a free ion, and cadmium sulfide (greenockite) the only mineral of this metal [4]. It is used as a raw material in the industrial sector in the production of battery electrodes, synthetic pigments, ceramics,

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glass, steel and non-ferrous metal coatings, accessories for solar energy production, and in agricultural products such as fungicides and fertilizers [5]. Cadmium enters into water sources mainly through anthropogenic activities: cement industry, electrolysis, electroplating, mining, alloys, paint factory, battery production, and petrochemical industries [6]. The Cd content in the surface sediments of the Coastal River located in the Puno Region, Peru, and in the bay or gulf of Lake Titicaca is 0.70 mg/kg and 0.03 mg L^{-1}, respectively, both being above the world and Peruvian Standards [7,8].

Health research has shown that consumption of foods containing cadmium can cause lung disease, nausea, vomiting, abdominal cramps, diarrhea, headache, kidney dysfunction, and cancer [3,5,9]. In order to mitigate cadmium poisoning, the United States Environmental Protection Agency (EPA) and the World Health Organization (WHO) have limited its maximum allowable concentration in drinking water to 0.003 mg L^{-1} [10,11]. Likewise, the Peruvian Ministry of Environment through Supreme Decree 004-2017 aimed to reduce pollution of water resources by setting a maximum allowable limit is 0.003 mg L^{-1}, and thus, the cadmium removal should be performed before discharge to the river sources using environmentally friendly technologies [12]. Due to this, various separation technologies such as coagulation, flocculation, flotation, ion exchange, adsorption, electrochemical treatment, and chemical precipitation have been implemented in order to remove heavy metals present in an aqueous solution. However, these processes have some disadvantages such as high investment cost, sensitivity to operation, higher energy consumption and sludge production [2,13]. These disadvantages led the scientific community to innovate new separation technologies within the framework of green, sustainable, and economically viable chemistry, such as bioadsorption [14].

Bioadsorption is presented as a physical–chemical process that consists of two unitary operations: adsorption and absorption of molecules and ions. It is considered to be a green and clean process due to the following characteristics: generates minimal sludge, is a reusable material, and allows for the recovery of sorbate. It can an economically viable method because it uses waste materials as adsorbents, such as fruit and vegetable peels, agricultural waste, tree leaves, sawdust, and yeast [2,14], as well as magnetic composites [15,16], shoe waste [17], and modified chitosan [18]. The specific processes that allow for the capture of heavy metals are extracellular and intracellular accumulation and precipitation of the cell surface through the functional group's carboxylic groups, alcohols, aldehydes, ketones, phenolics, and ether [2,19,20]. Several plants and woody materials have been used as adsorbents for the separation of heavy metals, including *Quercus leucotrichophora* leaves [19], plant leaves [20], pine bark [21], pine residues [22], cocoa residues [23], apple marc [24], *Ficus carica* leaves [25], bamboo leaves [26], biochar from maize straw [27], the bark and pith of the breadfruit tree [28,29], grapefruit tree leaves [30], lentil peel [31], acetic acid-modified peat [32], meranti wood [33] and leaves of *Artocarpus odoratissimus* [34]. These materials present chemical and morphological characteristics of adsorbents, notably the functional groups and porous structure, and are valuable for their applicability and efficiency in the removal of toxic metal ions [35].

On the other hand, nowadays, there is an environmental crisis that has highlighted the importance of generating processes that are environmentally friendly for the separation of contaminants from domestic and industrial effluents. In this sense, the use of adsorbents such as tree leaves is a key field of research [20]. In Peru, there are 37 species of bamboos from 8 genera in the regions of Pasco and Cusco that are home to the greatest diversity. However, the regions of Madre de Dios and Amazonas are the most productive, are marketed in their stalk form, and are generators of raw material for the production of cellulose, paper, and ethyl alcohol. Therefore, bamboo is a sustainable, abundant, and diverse resource with great potential for development [36]. In this sense, the objective of the present investigation was to evaluate the efficiency of bioadsorption of the bamboo leaves (*Bambusa vulgaris*) in the removal of the cadmium(II) ions from an aqueous solution. The effects of pH variation, adsorbent dose, initial concentration, and temperature variation on the adsorption process establish the foundation for technological transference and implementation of bamboo forest residues as adsorbent materials for the treatment of waters contaminated with cadmium(II). It has already demonstrated a removal efficiency of more than 90%, and a study of its morphological structure confirmed it is appropriate for the elimination of ions like Cd(II). Moreover, it is a low-cost process and simple technology that is very viable for countries like Colombia and Peru. The findings of this research will contribute to a better understanding of the phenomenon of adsorption of Cd(II) ions from aqueous solution through bamboo leaf forest residues, which may be beneficial for the development of high removal capacity, low cost, and sustainable bioadsorbents.

2. Methodology

2.1. Materials and reagents

Bamboo leaves (BL) were collected from Chanchamayo Province – Junin – Peru. Cadmium nitrate ($Cd(NO_3)_2$) was used to prepare the synthetic solution, and analytical grade sodium hydroxide (NaOH) and nitric acid (HNO_3) (LOBA Chemie 99.0%) were used to adjust the pH.

2.2. Design of experiments

To analyze the effects of the study variables, a full 2 K factorial design was administered, using two factors with three levels of variation: pH (2, 4, and 6) and temperature (15°C, 30°C, and 55°C). All experiments were performed in triplicate.

2.3. Preparation and characterization of biomass

The biomass was washed with twice distilled water, dried at 50°C for 72 h, ground, and sieved using a 1 mm sieve. The scanning electron microscopy–energy-dispersive X-ray spectroscopy (SEM-EDS) analysis was performed for the surface morphological characterization of the biomass, using a Hitachi SU8230 SEM with 10 and 20 μm magnifications.

2.4. Adsorption tests

Cd(II) adsorption tests were performed in series by batches, using adsorbent doses of 2 g L^{-1}, a concentration of 20 ppm, 170 rpm of agitation over 30 min, and temperature and pH conditions described previously in the experimental design. The concentration of residual Cd(II) in solution was determined by atomic absorption using an AGILENT AA 280FS atomic absorption spectrophotometer, and the removal efficiency (%) and removal capacity, q_e, (mg g^{-1}) was calculated by Eqs. (1) and (2):

$$\text{Efficiency (\%)} = \frac{C_i - C_f}{C_i} \times 100 \quad (1)$$

$$q_e(\text{mg/g}) = \frac{(C_i - C_f) \times V}{M} \quad (2)$$

where C_i is the initial concentration and C_f is the final concentration in ppm, V is the volume of the solution in L, M is the mass of the adsorbent in g, and q_e is the concentration of the adsorbate at equilibrium in mg g^{-1} [31].

2.5. Bioadsorption kinetics

The analysis of adsorption kinetics is important for the design, modeling, and explanation of both the sorbate transport process at the adsorbent interface and its bonding to the biomass surface, which refers to the physiochemistry at the surface [37,38]. For the kinetic study, the biomass was immersed in 150 mL of Cd(II) solution with 170 rpm of agitation at the experimentally optimized conditions for pH, initial concentration, adsorbent dose, and temperature. Aliquots were taken at specific time intervals (3, 8, 15, 25, 35, 50, 80, 100, 130, and 150 min). The concentration of the remaining Cd(II) in the solution was determined by atomic absorption at 283 and 306 nm. The data obtained were adjusted to the non-linear kinetic models described in Table 1.

2.6. Adsorption isotherms

Adsorption isotherms were evaluated with the aim of characterizing the separation and equilibrium of Cd(II) between the solid and liquid phases [40,41]. The adsorbent was in contact with 50 mL of contaminant solution at different concentrations (20, 40, 80, 120 and 200 ppm) at 170 rpm for 30 min under the experimentally optimized conditions for pH, adsorbent dose, and temperature. The isothermal data obtained were adjusted to the Langmuir and Freundlich models described in Table 2.

2.7. Thermodynamics of bioadsorption

The temperature variable (288, 303, and 328 K) is related to thermodynamic parameters: free energy Gibbs ($\Delta G°$), enthalpy ($\Delta H°$), and entropy ($\Delta S°$), which are indicators of

Table 1
Kinetic adsorption models

Model	Equation	Parameter
Pseudo-first-order	$q_t = q_e\left(1 - e^{-k_1 t}\right)$	q_e (mg g^{-1}): adsorption capacity at equilibrium q_t (mg g^{-1}): adsorption capacity at time t k_1 (min^{-1}): Lagergren's constant k_1 (g min^{-1}): pseudo-second-order constant
Pseudo-second-order	$q_t = \dfrac{t}{\dfrac{1}{k_2 q_e^2} + \dfrac{t}{q_e}}$	
Elovich	$q_t = \dfrac{1}{\beta}\ln(\alpha\beta) + \dfrac{1}{\beta}\ln(t)$	α (mg g^{-1} min^{-1}): adsorption rate β (g mg^{-1}): Elovich's constant related to the extent of surface coverage and activation energy in chemisorption

Source: based on the study of Huang et al. [39].

Table 2
Isothermal adsorption models

Model	Equation	Parameter
Langmuir	$\dfrac{1}{q} = \dfrac{1}{q_{\max}} + \dfrac{1}{b \times q_{\max} \times C_e}$	$q_{\max}$ (mg g^{-1}): maximum amount of Cd(II) retained in the adsorbent b: Langmuir constant related to the affinity of the adsorbent for the contaminant C_e: concentration of adsorbate in the equilibrium
Freundlich	$\log q = \dfrac{1}{n}\log C_e + \log K$	n: adsorption intensity of the adsorbent according to its heterogeneity K: Freundlich's constant, related to the adsorption capacity of the adsorbent

Source: based on the study of Chi et al. [27].

process feasibility and spontaneity. The experimental data were modeled through the equations described in Table 3 at the best condition for pH and adsorbent dose with an initial concentration of 20 ppm.

2.8. Statistical analysis

The overall 2 K full factorial design was evaluated with MINITAB 19 statistical software, choosing the following independent variables: pH and temperature; and the dependent variable was: removal capacity (% removal). Determining significant differences between means, a unidirectional analysis of variance was used, followed by Tukey's means test with a P-value < 0.05.

3. Results and discussion

3.1. Scanning electron microscopy

SEM analysis shows the morphology and microstructure of the BL surface. Fig. 1 presents a rough porous surface with wavy layers and small circular formations. This surface structure contributes to rapid adsorption of contaminants and is characteristic of lignocellulosic materials [43] since it allows for the permeability of the molecules to the interior of the adsorbent through its pores [40].

SEM micrographs of the BL surface morphology after adsorption are shown in Fig. 2. It was determined that Cd(II) ions were adsorbed on the porous and heterogeneous surface of the biomass by the action of metal ion exchange and the biomass functional groups [42]. These features were confirmed through the presence of cracks, surface corrugations, roughness, and heterogeneous surface [44]. Likewise, it was observed that the textural properties of the surface of the adsorbent are altered by the Cd(II) adsorption process [19]. The BL structure is similar to meranti sawdust, which also has considerable pore layers and presents a good possibility for cadmium(II) adsorption; likewise, meranti sawdust exhibits a surface change after adsorption, in which the pores are reduced and the porous surface is coated by the metal [33].

The spectrogram and the elemental chemical composition of the BL after removal, obtained by EDS, are shown in Fig. 3. The presence of heavy metal ions on the adsorption surface is identified with a mass percentage of 0.43% for the adsorbent under study, which is attributed to the formation of links between the active sites of the lignocellulosic material and ions. C and O were identified as the most abundant elements on the surface of the adsorbent with 39.52% and 59.52%, respectively. The presence of elements such as K, Ca, and Al is also evident in smaller quantities. The presence of C and O is characteristic of

Table 3
Equations for thermodynamic adsorption parameters

Model	Equation	Parameter
Van't Hoff	$\ln K = \frac{-\Delta H}{RT} + \frac{\Delta S}{R}$	$\ln K_{ads}$: on the abscissa axis T: temperature (K) on the ordinate axis $\Delta H/R$: slope of the line $\Delta S/R$: intercept with the ordered
Gibbs free energy	$\Delta G° = \Delta H° - T\Delta S°$	$\Delta H°$: enthalpy increase $\Delta S°$: increased entropy

Source: based on the study of Villen-Guzman et al. [42].

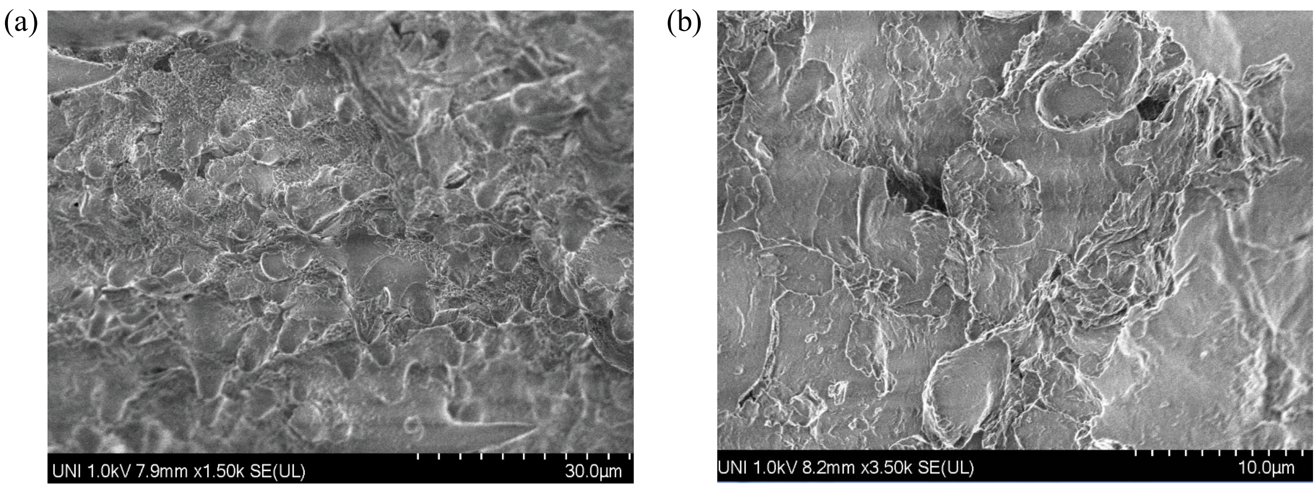

Fig. 1. Scanning electron microphotographs before adsorption 30 (a) and 10 um (b).

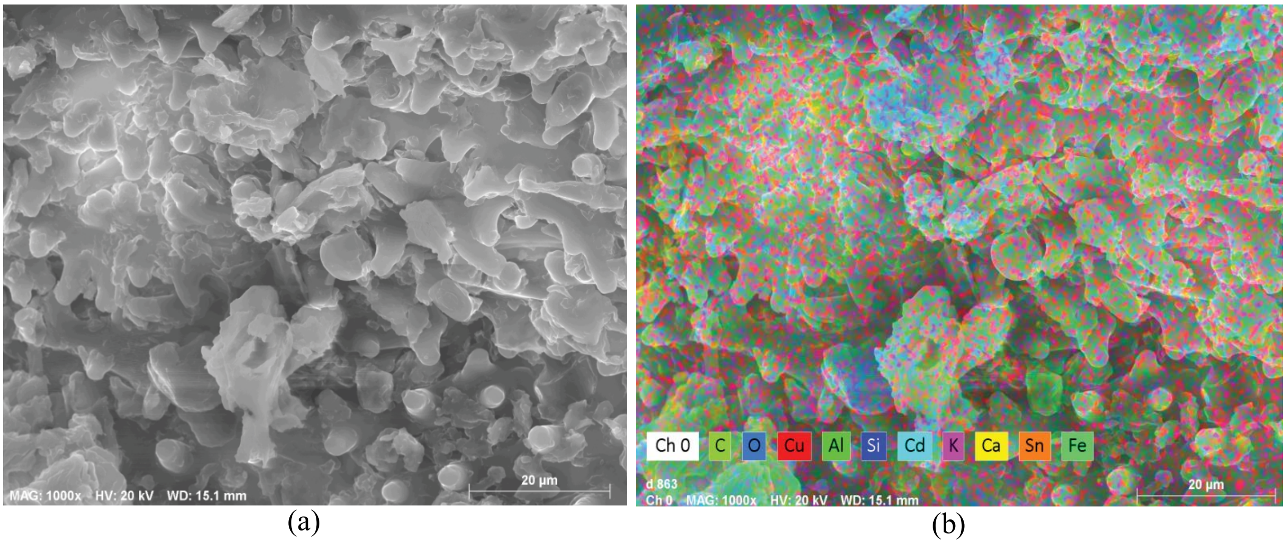

Fig. 2. Scanning electron microphotographs after adsorption 20 (a) and 20 um (b).

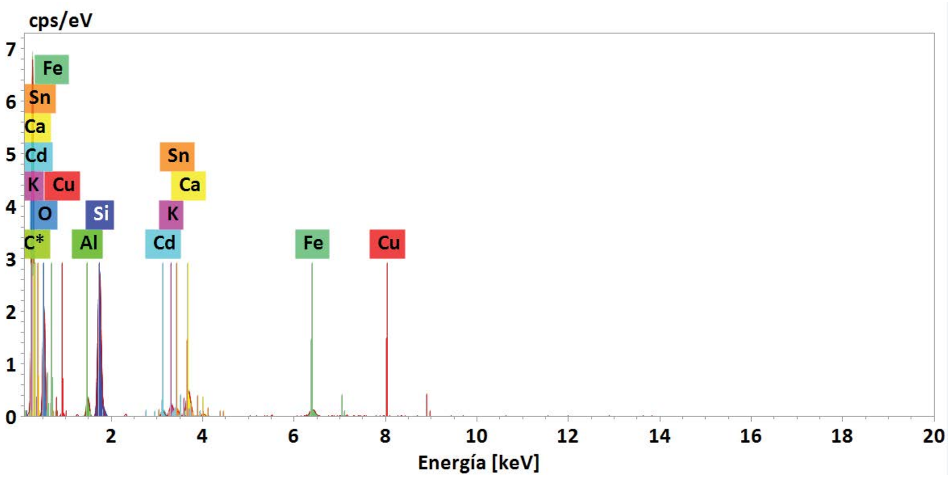

Fig. 3. Energy-dispersive X-ray spectroscopy spectrum of bamboo leaves after Cd(II) adsorption.

lignocellulosic materials, such as peanut peels [43], pine residues [45], yam, yucca, and plantain peels. [46]. The presence of these elements on the surface of the bamboo leaves are determinant for ion removal since the interactions with heavy metal ions are attributed to the carboxyl, hydroxyl, and amines functional groups that are basic components of biomaterials, such as carbohydrates, proteins, and phenolic compounds [42].

3.2. Effect of bioadsorbent dosage and initial concentration

The interactive effects between the adsorbent dose and the initial concentration on Cd(II) adsorption are shown in Fig. 4. It was found that the different doses of biomass supplied had a similar response in the first three concentrations. The 2 g L^{-1} dose showed an average removal of 94.42% but decreased as the concentration increased. Therefore, the lowest dose of adsorbent (2 g L^{-1}) was established at a concentration of 20 ppm. Considering these results, activated carbon from pine residues achieved an efficiency of 23.6% when evaluating a dose of 2 g L^{-1} [45], demonstrating that the bamboo leaves have a much higher performance. In the adsorption process, electrons are shared and exchanged between the active sites (–SH and $–NH_2$, strong chelating groups) and the Cu(II), Pb(II), and Cd(II) ions through covalent forces [47].

Ayub et al. [48] evaluated adsorbent doses between 0 and 20 g L^{-1} and found that the Cd(II) removal efficiency increased with the amount of adsorbent up to a certain level, achieving the best performance at 12.5 g L^{-1} with an adsorption percentage of 83.7%. They reported that the increase in the removal percentage was proportional to the adsorbent dose at low particle size, due to the increase in surface area and, therefore, to the availability of active sites [48]. Rafatullah et al. [33] used meranti wood in the removal of Cd(II) at an initial concentration of 100 ppm and found that when the adsorbent dose was increased from 0.5 to 5.0 g L^{-1}, the adsorption percentage increased; however, the

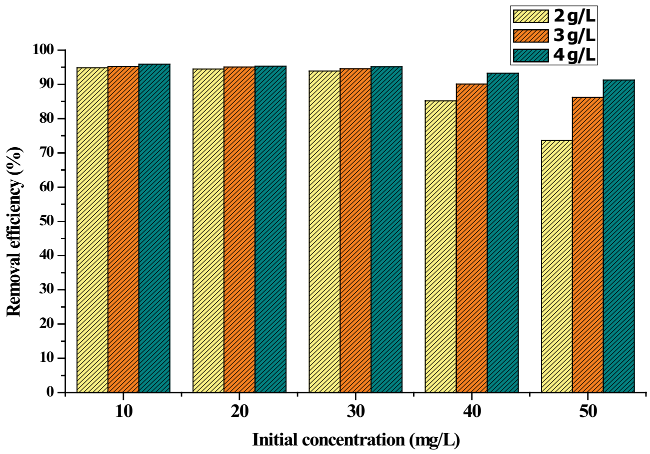

Fig. 4. Biomass dose effect.

adsorption capacity decreased considerably, obtaining the best performance at 1 g L^{-1}. For the initial concentration, Iqbal et al. [17] used shoe waste as a Cd(II) adsorbent and found that lower concentrations increased the adsorption capacity, which could be due to the relationship between total active sites on the surface and total metal ions in solution.

3.3. Effect of pH

The pH is a decisive parameter for optimizing the Cd(II) biosorption process because it influences the surface charges of the adsorbent and the degree of ionization of the adsorbate [49]. Fig. 5 shows the relationship between the solution pH and the efficiency of ion removal. At pH 4 and 6, the best removal percentages of 94.32% and 94.31% respectively, were obtained, and the efficiency decreased to 92.51% at pH 2. This behavior is due to the fact that at a low pH, some functional groups on the surface of BL (–COOH and –OH) are positively charged by protonation and, thus, reject the polar attraction of Cd(II) ions. This is because between pH 1 and 7, the predominant species is Cd^{2+}, which results in competition for the same negatively charged active sites on the surface of the biomass between H^+ and Cd(II) ions. As the pH value increases, the presence of OH^- increases, and therefore, the affinity of Cd(II) cations with the surface of the material increases [49–51].

Lim et al. [52] obtained a removal capacity of 3.5 mg g^{-1} at pH 7 using marang fruit pulp with an initial concentration of 10 ppm. Priyantha et al. [28] found that an increase in solution pH beyond 6.0 does not significantly increase the rate of metal removal when compared to ambient pH, reporting an adsorption capacity of 4,496 mg g^{-1} for breadfruit residues. When using coconut, nut, and almond shells, a removal percentage of 80.6% was achieved at pH 7, 72.5% at pH 6, and 83.7% at pH 6.5, respectively, [48]. Basu et al. [31] found that the adsorption efficiency of the lentil shell increased with pH, reaching the optimum of 18 mg g^{-1} between 5 and 6 for an initial concentration of 50 ppm.

3.4. Temperature effect and thermodynamic study

Temperature is an important variable in bioadsorption processes, as it facilitates the scaling up of the process, and thermodynamic study allows for an understanding of the nature and mechanisms of the adsorption process (endothermal/exothermal, favorability, and spontaneity of the process) [53,54]. Fig. 6 shows that the removal efficiency increases proportionally to the temperature, which implies higher molecular diffusion, higher molecule energy, a decrease of solution viscosity, and greater active site availability on the adsorbent surface due to pore dilation [19,38,55].

Table 4 shows the calculation of the thermodynamic parameters Gibbs free energy ($\Delta G°$), enthalpy variation ($\Delta H°$), and entropy change ($\Delta S°$) at an initial concentration of 20 ppm. The $\Delta H°$ values at pH 4 and 6 indicate an endothermic process and randomness, and these values of $\Delta H°$, 5.34 and 1.87 kJ mol^{-1}, respectively, suggest that Cd(II) bioadsorption can be characterized as a physical adsorption process [38]. The negative $\Delta G°$ values indicate that the process is spontaneous and viable, while the positive $\Delta S°$ value shows the greater randomness at the solid-solution interface in the contaminant removal and affinity for the adsorbents, confirming the findings of [42].

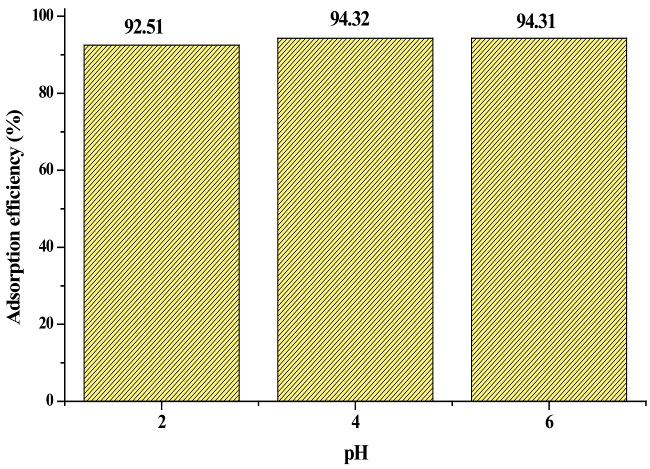

Fig. 5. Effect of pH on Cd(II) adsorption.

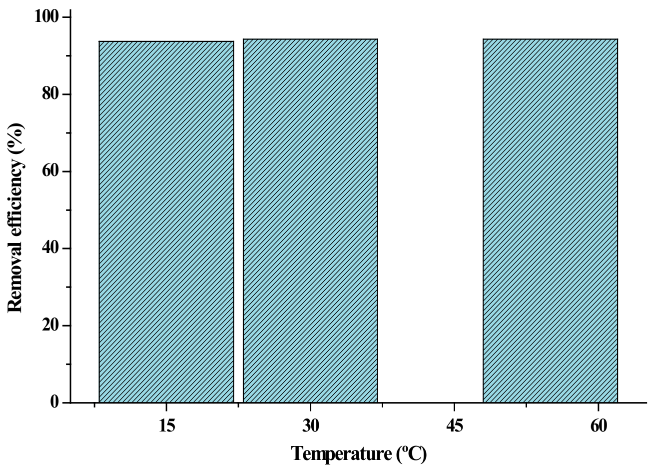

Fig. 6. Effect of temperature on Cd(II) adsorption.

Table 4
Thermodynamic parameters of Cd(II) adsorption

PH	Temperature (°K)	$\Delta G°$ (kJ mol⁻¹)	$\Delta H°$ (kJ mol⁻¹)	$\Delta S°$ (kJ mol⁻¹ K⁻¹)
	288	–6.761	–6.2325	–0.00183
2	303	–6.800		
	328	–6.830		
	288	–5.461	5.3390	0.0375
4	303	–6.024		
	328	–6.961		
	288	–6.770	1.8700	0.0300
6	303	–7.220		
	328	–7.970		

3.5. Statistical analysis

The study of the pH of a contaminated solution is a fundamental parameter in the adsorption process because it influences the adsorbate–adsorbent chemical properties and their interactions [56]. Temperature is one of the most important factors in adsorption processes, whose reactions are characterized by the thermodynamic equations [57]. Based on these two variables, the effect of pH and temperature on percentage of Cd(II) removal was analyzed. Using the MINITAB 19 program, the analysis of variance was applied to the experimental data and a p-value of 0.000, 0.000, and 0.002 was determined for the parameters pH, temperature, and pH-temperature interaction, respectively. Therefore, these values corroborate the significant influence on the process. Regarding these differences, the interactions of the independent variables as a function of Cd(II) adsorption efficiency were analyzed via the Tukey's mean test and are shown in Table 5.

In Table 5, the interactions between pH 4.0 and 6.0 values and temperatures 15°C, 30°C, and 55°C are observed, showing higher percentages of removal (93.75% to 94.32%). These results explain that at near-neutral pH, there is a greater removal of Cd(II), due to the anionic nature of the surface of the biomass. This phenomenon is attributed to the fact that when the concentration of hydrogen ions decreases, the competition between heavy metal cations decreases, and when the temperature increases, the dilation of the adsorbent pores increases. Likewise, an increase in the adsorption process temperature also makes the Gibbs' free energy (ΔG) more negative, thus increasing the degree of spontaneity [57].

Table 5
Interactions of the independent variables as a function of the percentage of Cd(II) removal, Tukey's mean test

pH	Temperature (°C)	Removal (%)	Grouping		
4	55	94.323	A		
6	30	94.305	A		
6	55	94.283	A		
6	15	93.745	A		
4	15	92.785	A	B	
2	15	92.505	A	B	
2	55	90.143	A	B	C
2	30	88.463		B	C
4	30	85.760			C

Removal percentages that do not share a letter are significantly different.

3.6. Adsorption isotherm

The adsorption isotherm describes the relationship between the equilibrium concentration of the contaminants and the adsorption charge on the adsorbents [58]. The geometric representation of the experimental data from the Cd(II) adsorption equilibrium process was fit to the Langmuir and Freundlich models and is shown in Fig. 7, while the model fit parameters are shown in Table 6. From the fit and the calculated values of R^2, it is observed that both models present a good fit of the data, noting that the Freundlich model fits them more precisely. It could be determined that the metal adsorption on the adsorbent surface is given by the formation of multilayers with non-uniform heat distribution and adsorption affinities, due to the heterogeneous structure of the bamboo leaves [41]. The parameter n of the Freundlich model, which relates the adsorption intensity, is higher than one, and thus, the removal process is considered favorable [51].

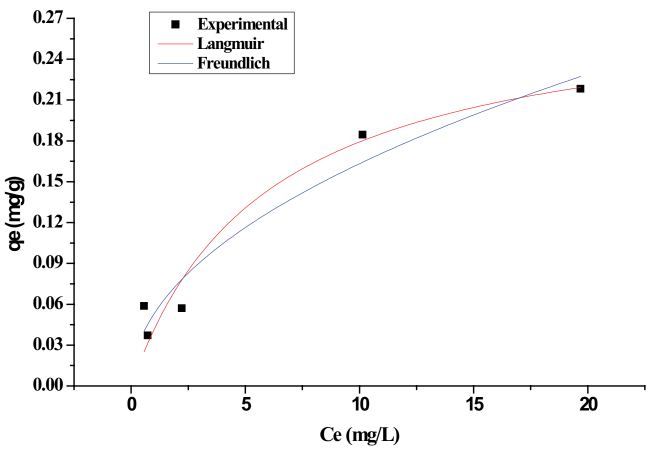

Fig. 7. Adjustment of the Cd(II) adsorption isotherm.

On the other hand, the affinity of Langmuir's model suggests that during the removal, there is no interaction between the pollutant molecules adsorbed on the adsorbent surface. Therefore, the amount adsorbed does not influence the adsorption rate, and a layer is formed on the surface until it reaches saturation, occupying each active site with a particle. All active sites on the surface have the same probability of being occupied by the adsorbate, and consequently, the adsorbent surface presents a finite number of energetically uniform and equal active sites [20,59]. The metal affinity for the adsorbent surface in terms of parameter *b* was low, which implies a low surface energy in the process and, consequently, a weak bond between the metal ions and the adsorbent. This indicates a physisorption mechanism and, hence, the recovery of the metal ions through easy desorption, which is an important criterion for selecting an adsorbent [60].

Table 6
Parameters of the Cd(II) adsorption isotherm

Model	Parameter	
Langmuir	q_{max} (mg g^{-1})	103.09
	b	0.20
	R^2	0.9151
Freundlich	K_f	0.05
	n	2.04
	R^2	0.9350

Table 7 presents the q_{max} values obtained in both previous studies and the present research for Cd(II) adsorption on different bioadsorbents.

3.7. Adsorption kinetics

Adsorption kinetics determine the contaminant removal rate as a function of solute residence time at the solid-solution interface [2]. Additionally, it establishes the adsorption mechanisms on the bioadsorbent surface, according to the mass transfer and chemical reactions [57]. In Fig. 8, the experimental data and modeling of the kinetic

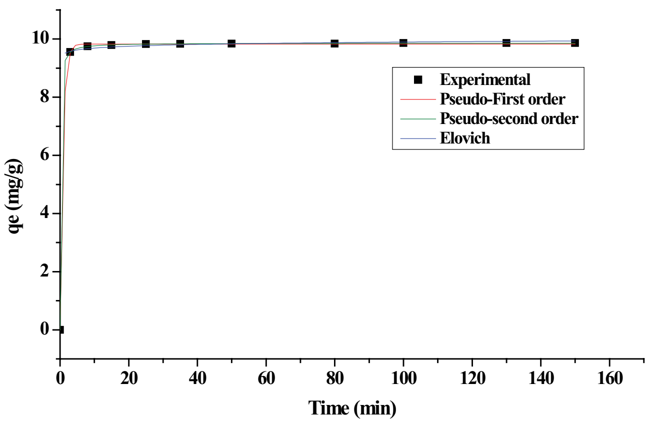

Fig. 8. Cd(II) adsorption kinetics.

Table 7
Comparison of q_{max} values

Bioadsorbent	q_{max} (mg g^{-1})	Source
Present study	103.09	
NaOH-modified oak waste	125.3	[51]
Pine activated carbon	167.3	[22]
Quercus leucotrichophora	3.71	[19]
Apple pulp modified with succinic anhydrous	91.75	[24]
Fig leaves	37.74	[25]
Commercially available activated carbon	17.3	[44]
Chitosan-tannin functional paper	813.01	[50]
Activated carbon from cornstalk	40	[55]
Barley husk	6.06	[61]
Barley husk ash	8.4	
Chitosan grafted with ethyl acrylate	1,111	[62]
Coconut shell	3.9119	[48]
Meranti wood	175.43	[33]
Surfactant-modified chitosan beads	125	[18]
Corn straw biocoal	38.91	[27]
Pyrolyzed magnetic biocoal at 600°C	16.44	[15]
Pyrolyzed magnetic biocoal at 800°C	14.32	
Fe-modified pyrolyzed magnetic biochar at 600°C $(NO_3)_3$	28.71	
Fe-modified pyrolyzed magnetic biocoal at 800°C $(NO_3)_3$	46.90	
Lentil peel	107.31	[31]

equations of pseudo-first-order, pseudo-second-order, and Elovich are shown. Rapid adsorption is observed in the first 15 min, due to the high availability of active sites in the adsorbent, and it becomes stable after 25 min.

Table 8 shows the fit parameters to the kinetic models evaluated. From Fig. 8, it can be determined that the pseudo-second-order model best describes the adsorption kinetics of Cd(II) on the biomass, and thus, it is inferred that the adsorption process is controlled by chemical reaction, based on ion exchange and complexation between the active centers of the adsorbent and the metal ion [55,63]. Rafatullah et al. [33], Takdastan et al. [51], and Sun et al. [50] also reported a good fit of the experimental kinetic data to the pseudo-second-order model. The adsorption capacity (q_e) was determined experimentally at each time interval and was also correlated with the kinetic models of pseudo-first-order and Elovich. These suggest that the rate of adsorption is controlled by a chemical reaction between the active centers of the bioadsorbent and the contaminant [64].

4. Conclusion

This study determined that Bamboo biomaterial presents a porous, rough, and corrugated morphology, making it very efficient for the removal of Cd(II) ions, and it achieved removal greater than 90% for all the evaluated conditions. The kinetic study indicated that the adsorption process is controlled by a chemical reaction between the active sites of the material and the metallic ion under study. From the isothermal study, it could be established that Cd(II) adsorption occurred in a heterogeneous way with variable adsorption energy depending on the surface coverage. From the thermodynamic parameters, it could be inferred that the adsorption process is endothermic, favorable, and spontaneous. This study is innovative in its evaluation of bamboo leaves forest residues as an effective and low-cost adsorbent for Cd(II) removal in aqueous solution, suggesting great potential for technological transfer in countries like Colombia and Peru.

Table 8
Calculated parameters of the adsorption kinetics

Model	Parameter	Value
Pseudo-first-order	q_{max} (mg g^{-1})	9.83
	k_1 (min^{-1})	1.189
	R^2	0.999
	SS	0.0118
Pseudo-second-order	q_e (mg g^{-1})	9.864
	k_2 (g min^{-1})	1.0477
	R^2	1
	SS	0.0016
Elovich	β	11.071
	α	3.5×10^{44}
	R^2	0.999
	SS	0.0063

SS is the sum of errors.

Acknowledgments

The authors thank the Universidad Nacional del Centro del Perú and Universidad de Cartagena (Colombia) for the support in the development of this work regarding laboratory, software use, and time contributed by their researchers. We are grateful to Michael James Stablein for the critical review of the manuscript.

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