



Sorption of Pb(II), Cd(II), and Zn(II) ions from aqueous solution using *Thaumatococcus danielli* leaves: kinetic, isotherm, and thermodynamic studies

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ABSTRACT

The toxicity of Pb²⁺, Cd²⁺, and Zn²⁺ ions in an aqueous solution cannot be over-emphasized. Therefore, it is essential to treat industrial wastewater containing these heavy metals before being discharged into the environment. In this study, we evaluated the sorption of Pb²⁺, Cd²⁺, and Zn²⁺ metal ions onto *Thaumatococcus danielli*. We studied the effects of different influential parameters such as contact time, pH, metal ion concentrations, and temperature. The batch sorption study revealed that the sorption process is pH dependent, with optimum pH obtained at 4.0 for Pb²⁺ and Cd²⁺ and 5.0 for Zn²⁺, respectively. The sorption equilibrium and kinetic rates studied revealed that the adsorption data best fit Freundlich isotherm and pseudo-second-order models, respectively. The q_{\max} values obtained are 95.215, 77.482 and 84.090 mg/g for Pb²⁺, Zn²⁺ and Cd²⁺, respectively. Thermodynamics analyses indicate that the metal ions sorption on *Thaumatococcus danielli* is feasible, spontaneous, and endothermic. The enthalpy values are 61.42, 42.17, and 41.34 kJ/mol for Pb²⁺, Cd²⁺ and Zn²⁺, respectively. Fourier-transform infrared analysis showed ionizable functional groups such as –OH, C=C, C≡C, C=O, C–O, and C–H, which could involve the metal binding. The results indicated that *Thaumatococcus danielli* could be a prospective sorbent for the sorption of Pb²⁺, Cd²⁺, and Zn²⁺ from polluted aqueous solution.

Keywords: *Thaumatococcus danielli*; Sorption; Pb²⁺; Cd²⁺; Zn²⁺

1. Introduction

Water pollution constitutes a significant threat to human health and animals due to the release of toxic and hazardous chemicals from various anthropogenic and industrial activities [1].

Clean water is essential in almost all human deeds, from domestic to industrial usage. Still, heavy metals in water bodies render them unfit for use because they tend to aggregate in living organs and become toxic.

Cadmium, for instance, is an essential metal for many industrial processes such as coating and plating,

rechargeable batteries, solar cells, alloys, and pigments. However, it is a toxic environmental element with high mobility [2]. The harmful effects of cadmium in the body include kidney problems, cancer wearing of bone, hypertension, lung dysfunction, and liver impairment damage [2]. It causes the poisoning of aquatic organisms and drastic changes in the marine ecosystem.

On the other hand, lead production is increasing globally because of its use in lead-acid batteries [3]. Soils and plant contamination leads to transcending the food chain affecting microorganisms and animals [3,4]. Lead exhibits a high degree of toxicity (whether inhaled or swallowed) in

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many organs, damaging the nervous, renal, reproductive, hematopoietic, and cardiovascular systems after ingestion, inhalation, or skin absorption [4].

The report also showed that lead(II) compounds are harmful contaminants to the biosphere, posing a detrimental risk to living organisms' survival even at low concentrations [5]. In humans, for instance, regular contact with lead has been found to cause edema, learning impairment in children, damage to organs, and distortion of the immune system [6].

Similarly, zinc is a vital element for living organisms' survival and a micronutrient in small amounts [7]. Nevertheless, persistent exposure to zinc could pose health risks for humans. At higher concentrations, zinc causes deformation of protein metabolism, arteriosclerosis damage, and damage to the pancreas [7]. Consequently, there is a need to reduce the concentrations of Pb^{2+} , Cd^{2+} , and Zn^{2+} ions in polluted water to tolerable concentration levels.

Interestingly, various techniques for treating polluted water include but are not limited to chemical precipitation, reverse osmosis, solvent extraction, coagulation, membrane separation, ion exchange, electrolytic processes, and ultrafiltration [8–10]. The disadvantages of these conventional methods include incomplete removal of pollutants, costly, time-consuming, sludge generation, and high energy requirements [8–10]. Thus, it is necessary to look for substitute options with low-cost operations that are simple to manage and do not generate sludge.

Hence, the sorption process is an effective and straightforward method for heavy metals pollutant removal which only requires minimal reagents and the possibility of recovery of the added biomass through the regeneration process [11,12]. However, the high cost of sorbent (activated carbon) for the sorption process has resulted in the continuous search for cheaper and more effective sorbents. Some sorbents successfully used to remove pollutants are γ -alumina nanoparticles and multi-walled carbon nanotubes [1], clarified sludge, rice husk ash, neem bark, chemically activated alumina [7], orange peel [8], fish scale [9], groundnut husk [10], maize wrapper [12], aerobic granules [13], and dried marine green [14]. *Thaumatococcus danielli* is a plant found in the forests in West Africa. Its uses are versatile. It has medicinal value, a sweetener, and food packaging. *Thaumatococcus danielli* is a non-tree (rhizomatous) plant that grows naturally [15].

In this study, we used the biomass of *Thaumatococcus danielli* leaf as a sorbent to eliminate Pb^{2+} , Cd^{2+} , and Zn^{2+} from an aqueous solution. We studied the influence of various factors such as the contact time, sorbent dosage, pH, and initial concentration of heavy metal ions to determine the optimum condition. Finally, the sorption isotherm and kinetic studies of Pb^{2+} , Cd^{2+} , and Zn^{2+} ions onto the prepared sorbent were studied and evaluated.

2. Experimental

2.1. Preparation of biomass

Thaumatococcus danielli (moimoi leaf) leaves used in this study were plucked from a small farm at Ago-Iwoye, Ogun State, Nigeria, and thoroughly washed with distilled water to remove dust and other impurities. The leaves dried

for two weeks at room temperature, crushed into smaller pieces to increase the surface area, carefully weighed into different masses, and stored until the time of use.

2.2. Preparation of stock solution

All chemicals and reagents used were of analytical grade. Standard stock solution (1,000 mg/L) of Pb^{2+} , Cd^{2+} and Zn^{2+} were prepared by dissolving $Pb(NO_3)_2$, $Cd(NO_3)_2 \cdot 4H_2O$, and $Zn(NO_3)_2 \cdot 6H_2O$ salts respectively in deionized water. The desired solutions were prepared by dilution of the stock solution. The pH was adjusted using 0.1 M HNO_3 and 0.1 M NaOH.

2.3. Characterization analyses

We examined the surface of *T. danielli* with FT-IR recorded at 400–4,000 cm^{-1} using a Shimadzu FTIR model 8400 S spectrophotometer to provide information on the nature of possible interactions between the functional groups of *T. danielli* and the metal ions. Scanning electron microscope (SEM) analysis was performed to investigate the morphology and particle size of the sorbent with the aid of Hitachi (Japan) S-3000H electron microscope with an accelerating voltage of 15 kV.

2.4. Batch sorption study

The batch sorption experiments were carried out from 0 to 3 h in a test tube at 27°C in a thermostat water bath. We contacted 0.5 g of *T. danielli* with 25 mL of 100 mg^{-1} of each prepared metal ions solution. The content was left for different periods, from 0–3 h. At a particular time, the samples were taken out from the bath, filtered, and the residual Cd^{2+} , Pb^{2+} , and Zn^{2+} ions concentration in solution were determined using flame atomic absorption spectrophotometer (FAAS) equipped with a flame burner (Perkin-Elmer analyst 700). The quantity of pollutant (QE) and the percentage sorbed were calculated using the equations below:

$$q_e = \frac{C_i - C_f}{m} \times V \quad (1)$$

$$\% \text{Sorbed} = \frac{C_i - C_f}{C_i} \times 100 \quad (2)$$

where the concentration of the initial pollutant used is C_i and C_f denotes the final concentration in mg/L, m stands for the mass of *T. danielli* used in g. V is the volume of the contaminants in L. We used different *T. danielli* dosages in this study (0.2 to 2.0 g) at 100 mg/L metal ions concentration to determine the effect of varying *T. danielli* dosage.

3. Results and discussion

3.1. FT-IR elucidation

The FT-IR spectra of *T. danielli* loaded with metal ions, and the sorbent was recorded in the range of

350–4,000 cm^{-1} (Fig. 1b). The functional groups prominent on FTIR spectra of *T. danielli* leaf are; OH stretching of the carboxylic group at 3,264 cm^{-1} , C–H stretch at 2,927.45 cm^{-1} , C=O stretching of conjugated acid at 1,770 cm^{-1} , C=C peak at 1,647.11 cm^{-1} , C–O stretch of esters at 1,200 cm^{-1} , and C–O of alcohols at 1,100 cm^{-1} . The presence of ionizable and electron-rich functional groups of O–H, C=C, and C≡C is likely the active sites that bind with the metals' positive ions (cations) [11,14]. There was a hypochromic shift due to the sorption effect of the metal ions on the sorption band of the free biomass.

The SEM visualize the biomass particles and the sorbent's microstructure nature, as shown in Fig. 1a. The SEM analysis of *T. danielli* revealed various sizes arranged

in a flower-like display. The particles have a diameter of 10–130 μm .

3.2. Effect of solution pH on sorption of metal ions

The effect of pH on the sorption of Cd^{2+} , Pb^{2+} , and Zn^{2+} ions, was done from 1–7, reacting 0.5 g of *T. danielli* leaf with 25 ml of 100 mg^{-1} of the tested metal ions. The result in Fig. 2a. The optimal pH is pH 4.0 for Pb^{2+} and Cd^{2+} and pH 5.0 for Zn^{2+} . Higher pH causes the precipitation of the metal hydroxides [12,16]. At lower pH, the active sites of the biomass protonate; hence, hydrogen ions, being positive ions, contend with the positive metal ions for binding with the biomass surface's active sites, resulting in low

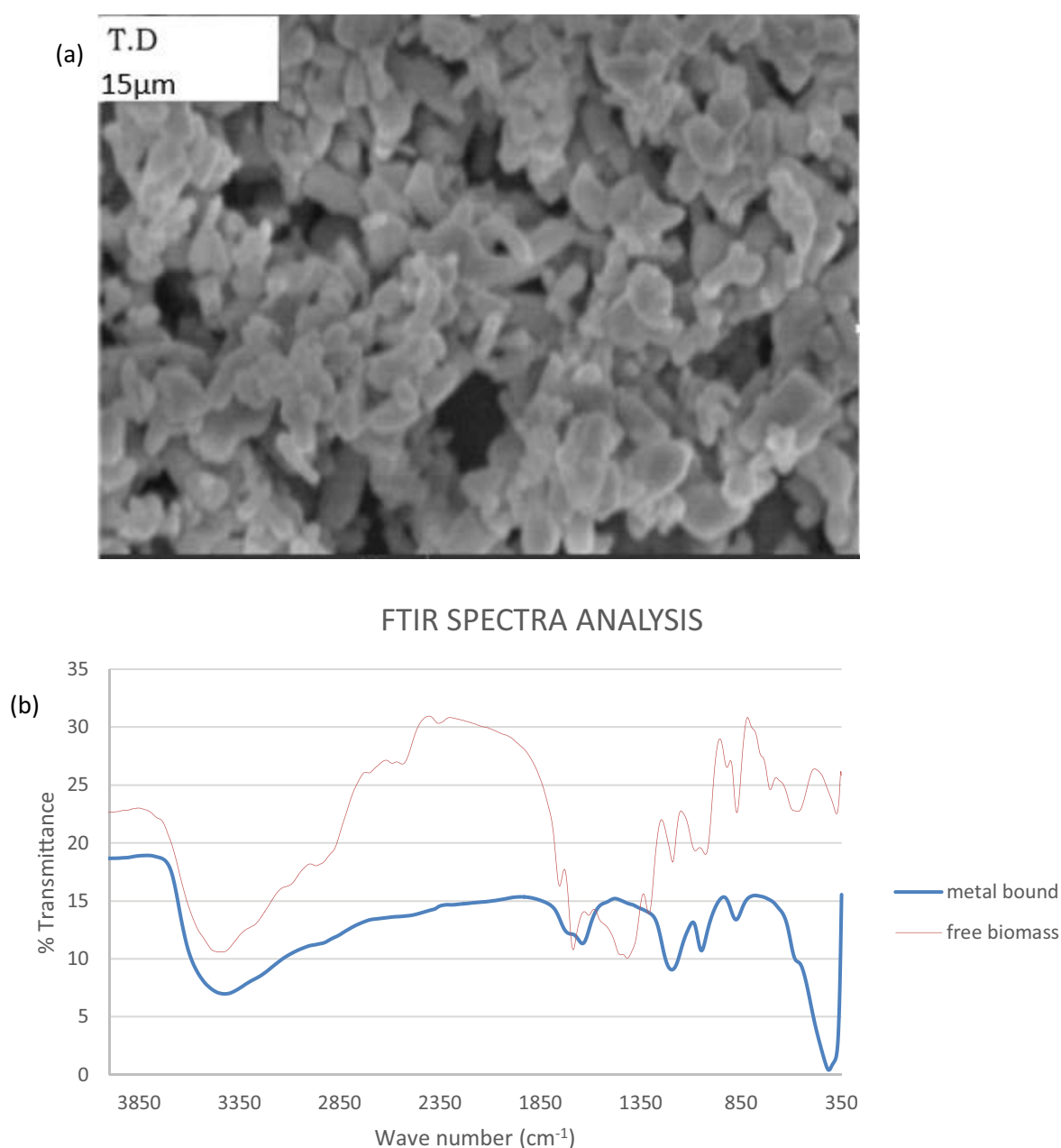


Fig. 1. (a) SEM image of *Thaumatooccus danielli* and (b) FT-IR spectra of the free and metal-bound TD leaf.

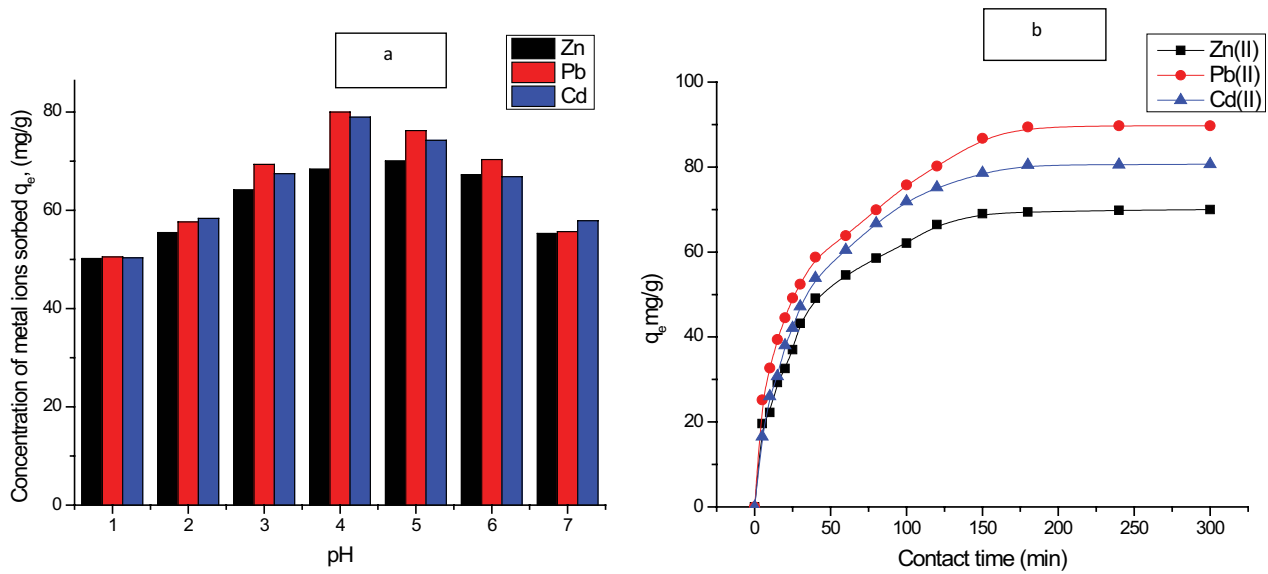


Fig. 2. (a) Effect of pH on sorption of (b) time-dependence plot for sorption of Zn^{2+} , Pb^{2+} and Cd^{2+} , Pb^{2+} and Zn^{2+} by TD Cd²⁺ onto the TD leaf.

sorption [12]. Literature also reveals that sorbent cell wall ligands are saturated with hydroxonium ions, and repulsive forces prevent metal ions from binding onto the biomass's surface [12,16]. Optimum sorption in this present study was established to be 92.00, 81.00 and 70.00 mg/g for Pb^{2+} , Cd^{2+} and Zn^{2+} , respectively. The results agreed well with those documented using the *Musa parasidiaca* flower for the sorption of the same metal ions [12].

3.3. Effect of biomass dosage

The sorbent dosage determines the sorption sites available for metal ions to adhere. Hence its quantity greatly influences the uptake of pollutants from the solution [17]. Therefore, varying the biomass used is crucial in sorption studies as it determines the sorbent efficiency for a given contaminant. The increase in metal ion sorbed observed with increasing sorbent dosage was due to the rise in available sites on the *T. danielli* surface, as shown in Fig. 3 and an increase in the number of the receptors on the sorbent surface. However, when the sorbent dosage is above the maximum values, a reduction in the amount of the pollutant sorbed could be noticed [18].

3.4. Kinetics study

Sorption kinetics were carried out to assess the efficiency of the sorption process with time. The kinetics of sorption is crucial in determining the rate at which sorption occurs and can also give helpful information about the sorption mechanism. However, sorption kinetics has been found to vary with different sorbents, as the sorption process could depend on the composition of the sorbent material. The sorption data of the metal ion at various contact times revealed that the number of metal ions sorbed increases as time proceeds, as depicted in Fig. 2b. The sorption process was

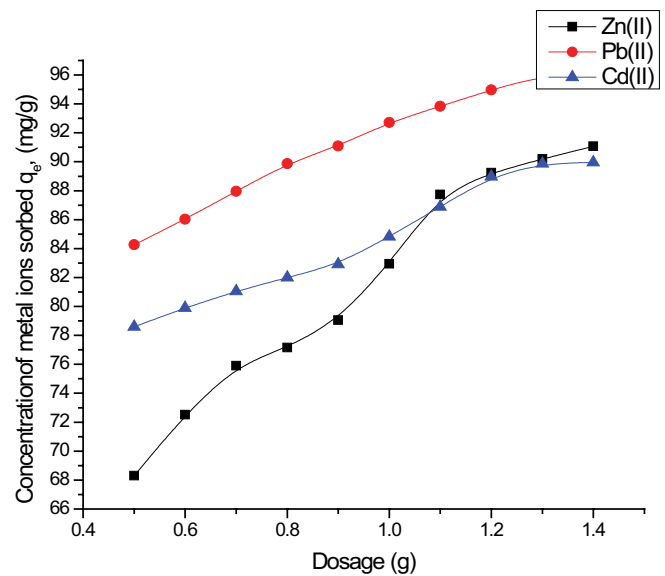


Fig. 3. Influence of sorbent's dosage on the sorption of Pb^{2+} , Zn^{2+} and Cd^{2+} by TD leaf.

initially rapid and gradually slowed down upon approaching equilibrium. The fast initial removal of the metal ions by the sorbent may be due to the availability of free binding sites on the surface of the *T. danielli* leaf [19]. The sorption rate becomes relatively steady as time progresses and then reasonably constant at 150 min for Zn^{2+} and Cd^{2+} . In comparison, the rate of sorption was pretty consistent at 180 min for Pb^{2+} (Fig. 2b). The difference in the equilibrium time might be due to the difference in affinity of the metal ions to the available active sites on the biomass surface. The data showed that the maximum quantity of the pollutants sorbed at equilibrium for the sorption processes are 88.04, 79.21, and 66.92 mg/g for Pb^{2+} , Cd^{2+} , and Zn^{2+} , respectively.

Four kinetic models were employed viz; pseudo-first-order, pseudo-second-order, Elovich, and intraparticle diffusion kinetic models as listed in Table 1 [20–23]. The models were used to understand the mechanisms of the sorption of the pollutants by the *T. danielli* leaf. The values obtained from these models are as listed in Table 2 using Fig. 4a–d.

From Table 3, it follows that the kinetics studies are best explained with the pseudo-second-order model with the highest values of R^2 , thus, suggesting that the sorption process proceeded via chemisorption. This corroborated closeness of the importance of the calculated sorption capacity of the pseudo-second-order with the experimental values. The calculated values of q_e from the pseudo-second-order are 85.22, 65.17, and 80.25 mg/g. Additionally, based on the values of $R^2 > 0.9$ as listed in Table 3, the Elovich equations seem to describe the sorption kinetics of the metal, which proceeds via ion exchange systems and thus suggest a chemical process.

3.5. Initial metal ion concentration and sorption isotherm

The driving force needed to overcome the mass transfer forces between the pollutant and sorbent depends mainly on the concentration of contaminants present in the solution at the beginning of the reaction, which plays

a vital role in the sorption process [10,24]. At higher concentrations, the uptake sites picked up the available pollutant more rapidly due to the quick diffusion of the pollutants particles into the available receptor sites of the sorbent. Results from experimental equilibrium sorption isotherm were analyzed with Langmuir, Freundlich, and Temkin models [25–27] as listed in Table 3.

The Langmuir model suggested monolayer sorption on the sorbent surfaces and that there are no interactions between adjacent molecules on the surface. Also, the Freundlich isotherm model is an empirical equation that describes the sorption process onto a heterogeneous surface. The model estimates the sorption intensity of the sorbate into the sorbent surface. On the other hand, the Temkin isotherm considers the interactions between sorbents and metal ions to be sorbed, based on the assumption that the free energy of sorption is a function of the surface coverage [28]. The linearized equation of the models is shown in Table 3. C_e is the equilibrium concentration (mg/L), q_e is the amount (mg/g) sorbed at equilibrium time, and q_{max} and b are Langmuir constants related to maximum sorption capacity (mg/g) and sorption energy associated with the heat of sorption (L/mg). If n and K_f are empirical Freundlich constants, indicative of sorption capacity and intensity, respectively. Temkin constants are α_T and β . The former is the maximum binding energy, while the latter is related to the sorption heat.

Table 1
Kinetic sorption models

S/N	Kinetics model	Linearized equation	References
1	Pseudo-first order	$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t$ [20]	
2	Pseudo-second-order	$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t$ [21]	
3	Elovich	$q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln t$ [22]	
4	Intraparticle	$q_t = k_{id} t^{1/2} + C_i$ [23]	

Table 3
Sorption isotherm models parameters

S/N	Isotherm model	Linearized equation	References
1	Freundlich	$\log q_e = \log K_f + \frac{1}{n} \log C_e$ [25]	
2	Langmuir	$\frac{1}{q_e} = \frac{1}{q_{max} K_L C_e} + \frac{1}{q_{max}}$ [26]	
3	Temkin	$q_e = \beta \ln a_T + \beta \ln C_e$ [27]	

Table 2
Kinetic parameters for the sorption of Zn²⁺, Pb²⁺ and Cd²⁺ using the TD leaf

Kinetic model	Parameters	Pb(II)	Zn(II)	Cd(II)
Pseudo-first-order	$q_{e,exp}$ (mg/g)	88.04	66.92	79.21
	k_1 (min ⁻¹)	1.432×10^{-2}	1.741×10^{-2}	1.711×10^{-2}
	R^2	0.951	0.866	0.930
Pseudo-first-order	$q_{e,cal}$ (mg/g)	71.43	87.11	68.79
	k_2 (g/mg·min)	3.95×10^{-4}	5.18×10^{-4}	4.18×10^{-4}
	R^2	0.994	0.997	0.996
Elovich	A	-7.571	-8.599	-7.571
	B	17.71	14.62	17.51
	R^2	0.977	0.972	0.981
Intraparticle diffusion	k_d (mg/g·min)	2.685×10^{-8}	2.52×10^{-9}	6.03×10^{-14}
	B	17.71	14.62	17.50
	R^2	0.977	0.9712	0.981

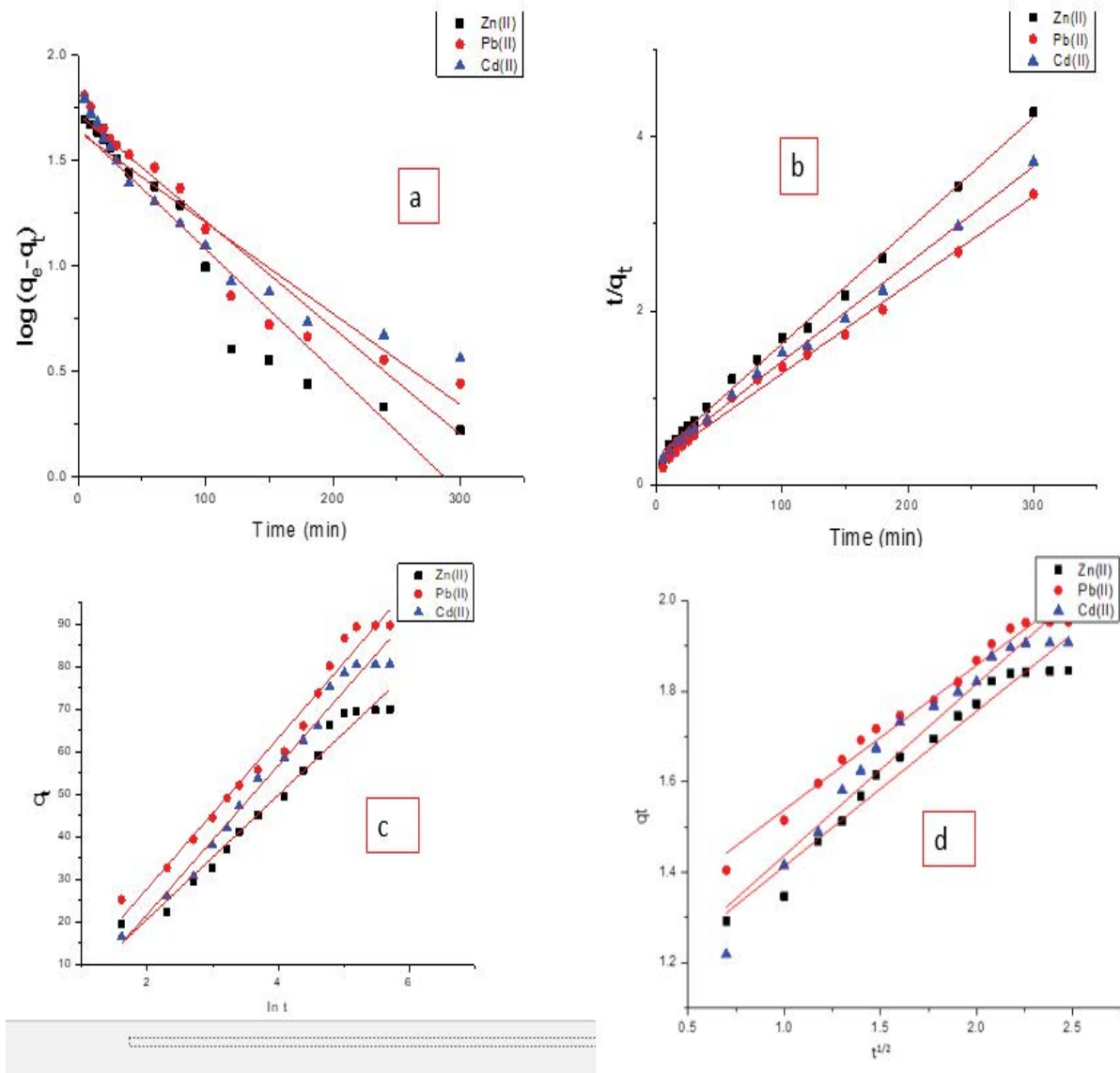


Fig. 4. Plots of (a) pseudo-first-order, (b) pseudo-second-order kinetic, (c) Elovich and (d) intraparticle kinetic models of the sorption of Zn²⁺, Pb²⁺ and Cd²⁺ using TD leaf.

Fig. 5 shows the plots of these isotherms, while the values of their constant as generated are presented in Table 4. Freundlich isotherm model with the highest correlation coefficient (R^2) value gave the best fit indicating that the sorption mechanism occurs via multilayer diffusion of the pollutants onto the sorbent surface.

The equilibrium capacity (QE) increases with the concentrations of the pollutants. The K_f values obtained for Pb²⁺, Zn²⁺, and Cd²⁺, are 10.69, 10.68, and 8.98, suggesting that Cd²⁺ had a greater affinity toward the *T. danielli* leaf biomass when compared with Pb²⁺ and Zn²⁺ (Table 5). Also, the Langmuir model obtained the q_{max} values are 95.215, 77.482, and 84.090 mg/g for Pb²⁺, Zn²⁺, and Cd²⁺ as shown in Table 4. The comparison of Cd(II), Pb(II) and Zn(II) maximum sorption capacity of different sorbents with *T. danielli* leaf biomass is shown in Table 6.

3.6. Thermodynamics evaluations

Experiments were performed in the temperature range of 293–323 K to evaluate the thermodynamic parameters while keeping other variables constant. The free energy change (ΔG) was estimated using the equation below:

$$\Delta G^\circ = -RT \ln K_c \tag{3}$$

where the absolute temperature is given as T (K) and K_c is the equilibrium constant estimated from the relationship below:

$$K_c = \frac{C_{ad}}{C_e} \tag{4}$$

Table 4
Isotherm parameters of the sorption of Pb²⁺, Zn²⁺ and Cd²⁺ by TD leaf

Isotherm model	Parameter	Pb(II)	Zn(II)	Cd(II)
Freundlich	N	1.135	1.136	1.169
	K_f (mg/g)(mg/L) ^{1/2}	10.683	8.978	10.692
	R^2	0.977	0.982	0.992
	S.D	0.074	0.073	0.073
Langmuir	q_{max} (mg/g)	95.215	77.482	84.090
	K_L (L/mg)	-3.38×10^{-2}	-3.42×10^{-2}	2.76×10^{-2}
	R^2	0.893	0.852	0.860
	S.D	0.00641	0.0077	0.0062
Temkin	α_T (L/mol)	0.880	0.917	0.911
	β (J/mol ²)	29.407	24.218	27.286
	R^2	0.965	0.975	0.963

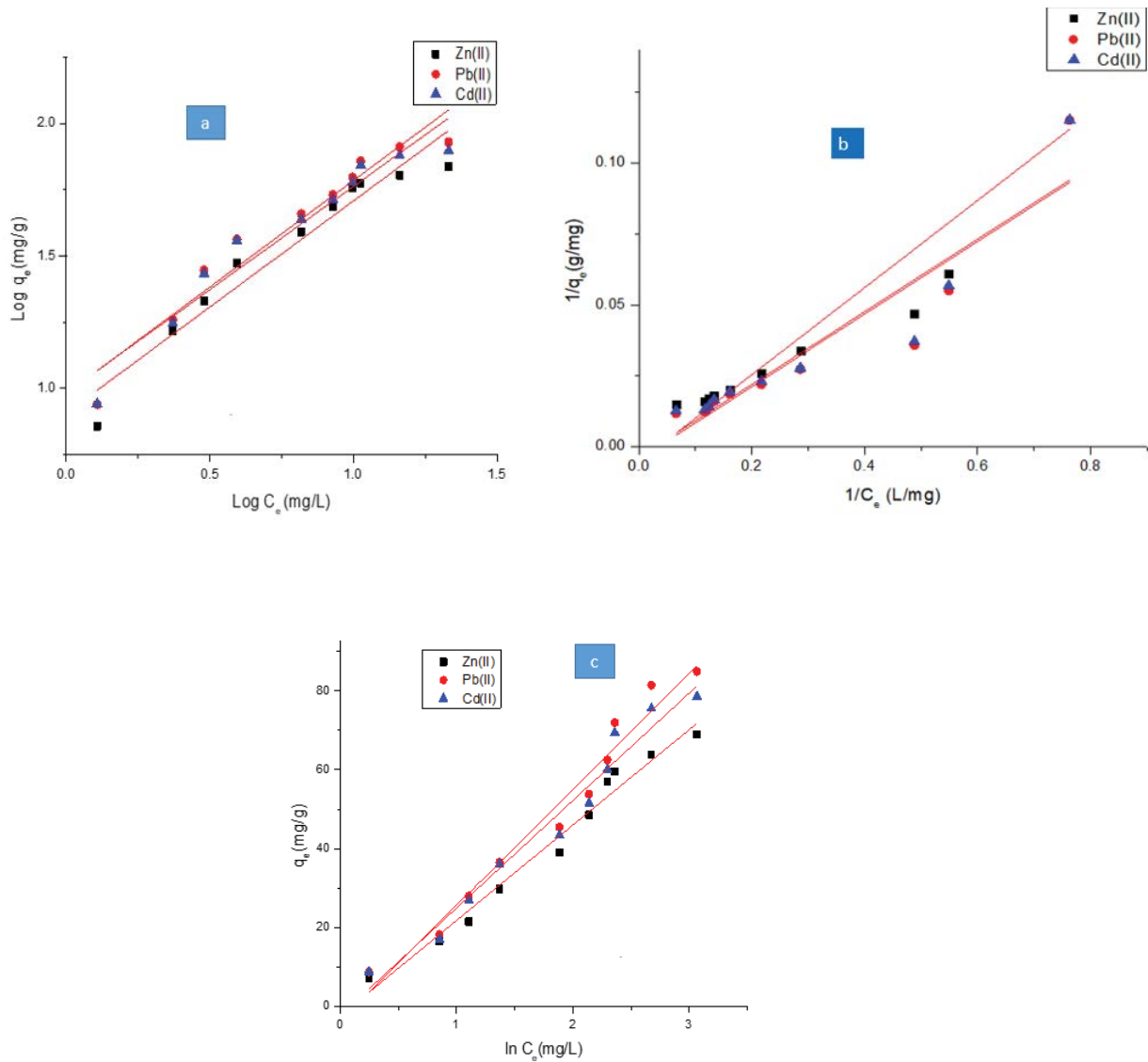


Fig. 5. Plots of (a) Freundlich, (b) Langmuir, and (c) Temkin isotherms of the sorption of Pb²⁺, Zn²⁺ and Cd²⁺ by TD leaf.

Table 5
Thermodynamic parameters of Pb²⁺, Zn²⁺ and Cd²⁺ sorption by TD leaf

Metal ion	ΔH (kJ/mol)	ΔS (J/mol·K)	E_a (kJ/mol)	ΔG (J/mol)						
				293 K	298 K	303 K	308 K	313 K	318 K	323 K
Pb	61.42	214.45	61.42	148.7	240.5	356.4	462.7	536.5	752.4	766.9
Cd	42.17	147.85	42.17	85	162.1	291.8	355.8	489	454.5	476.2
Zn	41.34	141.15	41.34	63.3	50.72	122.2	226	337.5	374	387.6

The concentrations of pollutants at equilibrium (mg/L) and the sorbed concentration by the sorbent are C_e and C_{ad} respectively.

The thermodynamic parameters, enthalpy, and entropy were obtained using Van't Hoff equation.

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \tag{5}$$

Substituting Eq. (3) in (5), we obtained Eq. (6):

$$\ln K_c = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{T} \tag{6}$$

Gibbs's free energy change (ΔG) measures in J/mol indicate the spontaneity and feasibility of the sorption process. The enthalpy change (ΔH) measures in kJ/mol give information about the exothermic or endothermic nature of the adsorption process, and entropy change (ΔS) measures in J/mol·K represents the degree of randomness of the adsorption process. T is the absolute temperature in K and R is the gas constant in J/mol·K. When the enthalpy change value is positive, it signifies an endothermic sorption process and can be favored by an increase in temperature, while a negative value of enthalpy change indicates an exothermic process favors a decrease in the temperature.

The impact of temperature on the sorption of Pb²⁺, Zn²⁺, and Cd²⁺ on the surface of *T. danielli* leaves is shown in Fig. 6. The sorption of the metal ion is found to increase with an increase in temperature. The thermodynamic parameters of enthalpy and entropy were obtained from the slope and the intercept in Fig. 7. The enthalpy changes obtained are 61.42, 42.17, and 41.34 kJ/mol for Pb²⁺, Cd²⁺, and Zn²⁺, respectively (Table 5). The positive values of the enthalpy indicate that the process is endothermic and requires an input of energy to proceed. The sorption process was spontaneous, demonstrating the feasibility of the sorption process.

The entropy values are higher than the value reported when the *Musa parasidiaca* flower was used to uptake the same metal ions from an aqueous solution [29] which indicates that the process is more spontaneous. Generally, the value of ΔG° for a physio-sorption process range between -20 and 0 kJ/mol, whereas values between -80 and -400 kJ/mol signify the chemisorption process [30]. The values of ΔG° obtained in the present study ranged from -0.0633 to -0.766 kJ/mol, corresponding to a spontaneous physical sorption process. The activation energy E_a is an essential factor in reaction rate determination, if the value is significant, the reaction is slow, and vice versa. The relationship

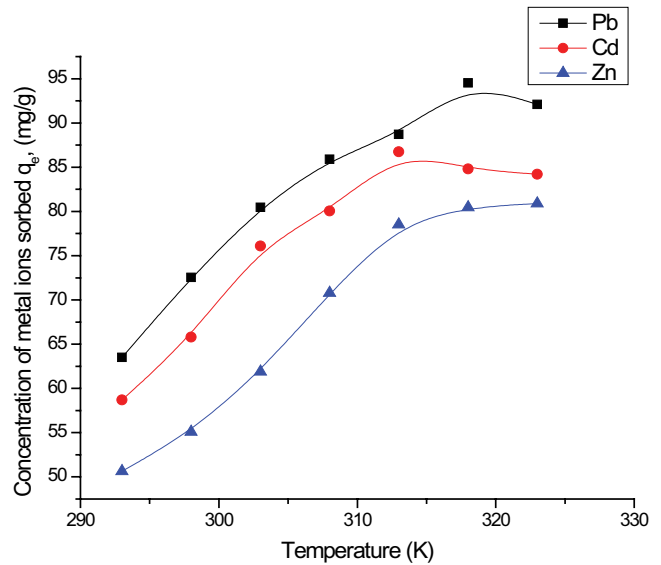


Fig. 6. Effect of temperature on the sorption capacity of TD on Pb²⁺, Zn²⁺ and Cd²⁺.

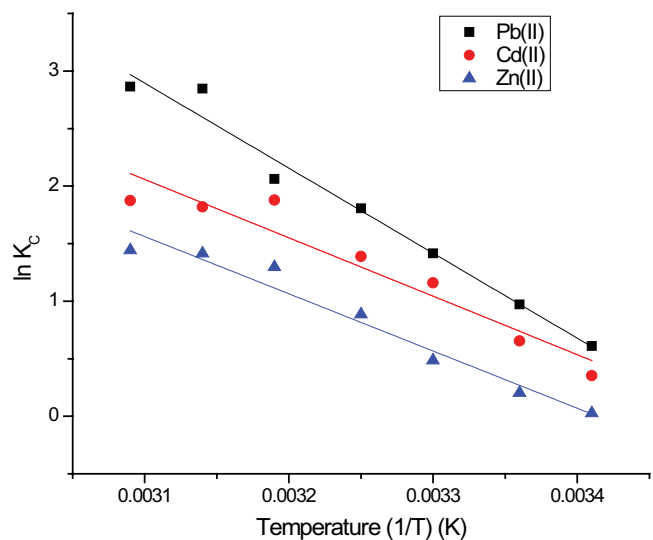


Fig. 7. van't Hoff plots for the sorption of Pb²⁺, Cd²⁺, and Zn²⁺.

between equilibrium constant K_c and activation energy E_a (in J/mol) can be established using the Arrhenius equation as shown in Eq. (7). A is the pre-exponential constant factor that correlates with the empirical relationship

Table 6
Comparison of Cd(II), Pb(II) and Zn(II) maximum sorption capacity of different sorbents

Sorbents	Sorbate	q_e (mg/g)	Optimum pH	References
<i>Musa parasidiaca</i>	Cd(II)	192.31	6	[29]
	Pb(II)	–144.72	6	
	Zn(II)	–847.46	6	
Rice husk	Zn(II)	20.8	3.5	[31]
<i>Mirabilis jalapa</i>	Cd(II)	38.461	6	[32]
	Pb(II)	23.461		
Algae	Cd(II)	2.52	5	[33]
	Pb(II)	3.08	6	
	Pb(II)	2.60	6	
Razor clam shell	Cd(II)	4.24	6	[34]
	Pb(II)	3.76	6	
	Zn(II)	9.17	6	
Oyster shell	Cd(II)	8.91	6	
	Pb(II)	0.73	6	
	Zn(II)	8.17	6	
<i>Azolla filiculoides</i> (treated with H ₂ O ₂ /MgCl ₂)	Pb(II)	228	5.5	[35]
	Cd(II)	86	6	
	Zn(II)	48	6.7	
Canola biomass	Cd(II)	25.86	7	[36]
	<i>Thaumatococcus danielli</i>	Pb(II)	95.2	
	Cd(II)	84.09	4	Present study
	Zn(II)	77.482	5	

between rate constant and temperature. The energy of activation is obtained via slope $-E_a/R$ of the straight line plot of $\ln K_c$ vs. $1/T$.

$$\ln K_c = \ln A - \frac{E_a}{RT} \quad (7)$$

The energy of activation was between 61 and 41 kJ/mol, suggesting that the sorption process is relatively slow as reported by [29], indicating that the present study is diffusion controlled as given by the value of the activation energy as shown in Table 6. Also, comparatively with other sorbents [31–36], *T. danielli* can serve as a suitable sorbent for the sorption of the reported metal ions.

4. Conclusion

The batch study investigates the sorption of Pb²⁺, Cd²⁺, and Zn²⁺ onto *Thaumatococcus danielli* surface under different reaction conditions such as contact time, pH, metal ion concentrations, and temperature. From the results obtained, we can infer that pH is one of the critical factors that affect the rate of sorption of Pb²⁺, Cd²⁺, and Zn²⁺ by *Thaumatococcus danielli*. Maximum sorption occurred between pH 4.0 during the sorption of Pb²⁺ and Zn²⁺ and 5.0 for Cd²⁺ removal by *T. danielli* leaf. We found equilibrium time for sorption of Pb²⁺, Zn²⁺, and Cd²⁺ from an aqueous solution achieved in the range of 150 to 180 min, and the experimental data fit the pseudo-second-order model. In contrast, the sorption

isotherm study showed that the Freundlich model provided the best fit. The results suggest that the *Thaumatococcus danielli* leaf is an efficient sorbent for deleting Pb²⁺, Zn²⁺, and Cd²⁺ from an aqueous solution.

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