Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2012.749186

51 (2013) 4390–4401
June

Taylor & Francis
Taylor & Francis Group

Insight to rapid removal of Pb(II), Cd(II), and Cu(II) from aqueous solution using an agro-based adsorbent *Sorghum bicolor* L. biomass

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Received 24 September 2012; Accepted 8 November 2012

ABSTRACT

The present study proposed the adsorption characteristics of Pb(II), Cd(II), and Cu(II) on to *Sorghum bicolor* L. (commonly, Charee in Pakistan) biomass from aqueous solutions. The influence of different process parameters, such as the adsorbent dose, solution pH, contact time, agitation speed, and initial metal ion concentration, were studied thoroughly to evaluate optimum conditions for adsorption. Maximum adsorption for all metal ions has taken place at pH 5.0–6.0. Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich isotherm models in a nonlinear fashion were used to explain the phenomenon. Maximum adsorption capacity of *Sorghum bicolor* L. biomass was 6.289 mg/g, 7.87 mg/g, and 4.34 mg/g for Pb(II), Cd(II), and Cu(II), respectively. Adsorption mechanism was explored by pseudo-first-order and pseudo-second-order kinetic models and it was found that the process followed pseudo-second-order kinetics. Thermodynamic study indicated the process favorability. The study concluded that the *Sorghum Bicolor* L. can be an effective adsorbent for removing toxic metals from water owing to the fine adsorption capacity.

Keywords: *Sorghum Bicolor* L.; Nonlinear isotherms; D–R model; Mean free energy; Thermodynamics

1. Introduction

Increasing levels of heavy metals in water streams is a major concern in several developing countries. Industrial activities, the major source of heavy metal pollution in water, thus, seriously damage the aqueous environment [1–4].

Cadmium is enlisted in the most toxic metallic pollutants. Various industrial sources such as electroplating, smelting, pigments, plastics, battery, mining, and refining processes contribute to cadmium pollution [5,6]. It is recognized as a human carcinogen [4]. Intake in very small amounts can also cause health problems such as hypertension. The permissible level suggested by EPA for divalent cadmium ions in water is 5 μg/L [7].

Lead, metallic specie, has been regarded as a persistent environmental pollutant [8]. Inorganic lead arising from a number of industrial and mining sources occur in water in the divalent state [9]. Almost all of its compounds are considered to be toxic which usually affect the gastrointestinal tract and nervous system [10]. The permissible level given by EPA for divalent lead ions in water is 5 μg/L [4].

Copper is one of the most widely used metals and is reported to be present in metal bearing industrial effluents [11]. The suggested EPA limit of cupric ions in industrial effluents is 1.3 ppm [12]. Long-term

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exposure causes irritation of nose, mouth, and eyes, stomachache, neurotoxicity, and lung cancer [4].

Various technologies are being used for removal of metallic pollutants from water such as alum and iron coagulation, lime softening, nanofiltration, reverse osmosis, electrodialysis, foam flotation, solvent extraction, and adsorption on natural and artificial materials [13–15]. Coagulation and lime softening have less removal efficiency and produce a large amount of chemical sludge. Adjustment of pH and pre-oxidation may also be needed for the said processes. Technologies like nanofiltration, reverse osmosis, and electrodialysis have high removal efficiency but involve high capital and running cost, and high tech maintenance [16].

The search for cost-effective technologies involving the removal of heavy metals from aqueous systems has attracted attention towards adsorption. The advantages of this method are high removal efficiency, low capital and running cost, minimization of toxic sludge, and regeneration of the adsorbent. Ion exchange, chelation, and surface binding by physical and chemical linkages govern the adsorption mechanism. Sizable information is available on materials having the ability to adsorb and remove metals from aqueous systems. Most of these materials are of natural origin, such as crop residues, plant products, or geological deposits. Byproducts of industrial processes are also considered [16]. Agricultural wastes have proved to be very useful and low-cost adsorbents for the removal of metals [17].

Sorghum biomass has been used in this study as a cost-effective adsorbent for metal remediation. Sorghum biomass is available as a plentiful waste agro-material because it is the fifth major cereal crop grown in the world [18]. The study includes the optimization of various process parameters, i.e. adsorbent dosage, pH, contact time, agitation speed, etc. Besides, various equilibrium models, kinetic models, and thermodynamic parameters were used to explain the mechanism.

2. Materials and methods

2.1. Preparation of adsorbent

Fresh *Sorghum bicolor* L. was collected from local market of Lahore, Pakistan. Later, the mass was washed with distilled water and subsequently dried in an incubator at 70˚C for about 8–9 h till constant mass. The material was ground to a fine powder in a laboratory grinder and was sieved in the particle size range of 60–80 mesh (ASTM). The processed material was stored in airtight plastic containers.

2.2. Chemicals, equipment, and apparatus

High purity chemicals and reagents, purchased from Sigma–Aldrich, Inc., were used during the study. The glassware was thoroughly washed with chromic acid, caustic soda, soda ash, tap water, and distilled water, in that order, and dried in an oven prior to use. Batch experiments were performed in conical flasks (250 mL) on top of orbital shaker (VORTEX Model-OSM-747). The pH was adjusted with NaOH (0.1 M) or HCl (0.1 M) solutions using a digital pH meter (HANNA, Model-8417). Perkin Elmer atomic absorption spectrophotometer (Model-AAnalyst 100) was used to determine the concentrations of Pb(II), Cd(II), and Cu(II) at 283.3, 228.8, and 324.8 nm. Fourier-transformed infrared spectrometer (FTIR) (Perkin Elmer Spectrum-RX1) was used to characterize the adsorbent.

2.3. Optimization of process parameters

Using the initial concentration of 50 mg/L for Pb(II), Cd(II), and Cu(II) ions, a series of experiments were performed to check the effects of various process parameters (adsorbent dose, contact time, pH, and agitation speed) on metal adsorption. The effect of a certain parameter was studied by varying it gradually keeping all other parameters constant. The glassware used in the study was successively washed with acid and distilled water and then, oven-dried at 105°C for 1 h. Atomic absorption spectrometer was used for the analysis of Pb(II), Cd(II), and Cu(II) ions concentration after adsorption under certain conditions. The effect of adsorbent dose was studied by varying the adsorbent amount from 0.2 to 1.8 g/50 mL. Variation of pH was made from 1 to 9 to investigate the optimum pH for metal adsorption. The effect of contact time and agitation speed on metal adsorption was studied under gradually varied conditions of 1–45 min (at different initial metal ion concentrations, i.e. 25, 50, 100, and 200 mg/L) and 50–250 rpm for contact time and agitation speed, respectively. Effect of temperature was also studied for the temperature range 293–353 K.

2.4. Study of adsorption isotherms

Solutions of varying concentration (20–100 mg/L) of Pb(II), Cd(II), and Cu(II) ions were taken in eight Erlenmeyer flasks (250 mL). Adsorption of metal ions from all these solutions was carried out under the optimum conditions obtained from the prior study of process parameters. Langmuir (Eq. (1)), Freundlich (Eq. (2)), and Temkin (Eq. (3)) isotherms were plotted and their corresponding parameters were calculated from their respective plots.

3. Results and discussion

3.1. Characterization of adsorbent

Ground and dried sorghum biomass (*Sorghum bicolor* L.) was subjected to FTIR analysis for its characterization in terms of functional groups (adsorption sites). The spectrum provides the absorbance peaks at 1726.29, 1517.98, 1446.61, 1332.81, 1238.30, 1157.29, and 1055.06 cm^{-1}, all being stretching of carboxyl group [19]. Another broad peak at 3284.77 cm^{-1} indicates the presence of hydroxyl group. The FTIR spectrum illustrating all this data is shown in Fig. 1.

3.2. Effect of adsorbent dose

The effect of adsorbent dose on Pb(II), Cd(II), and Cu(II) was studied by varying the amount of adsorbent from 0.2 to 1.8 g/50 mL for each of the metal ion individually at neutral pH for time interval of 25 min. Effect on adsorption due to variation in adsorbent dose is illustrated in Fig. 2 Maximum adsorption of Pb(II), Cd(II), and Cu(II) were 89.76, 53.07, and 55.02% for the dose of 1.0 g/50 mL for lead and cadmium, respectively, and 0.8 g/50 mL for copper. The increase in adsorption with the increase in adsorbent dose is attributed to the availability of adsorption sites for metal adsorption. It was also observed that after certain value of dose, the adsorption of metals decreases or remains constant with further increase in adsorbent dose, which indicated that there exist chemical equilibrium between adsorbent and adsorbate.

3.3. Effect of pH and agitation speed

To study the effect of pH is of prime importance as it controls the adsorption at adsorbent–solution interface. pH affects both the biomass and the metal ions present in the solution. Experiments were conducted varying the solution pH from 1 to 9 while rest of the factors were kept constant. The maximum removal of Pb(II), Cd(II), and Cu(II) was noted at pH range 5–6 as illustrated in Fig. 3. At basic pH (>7), metal ions precipitated out as their respective hydroxides which provides hindrance in adsorption process. Less removal of metal ions was also observed at low pH range (<3) due to the repulsion of cations with

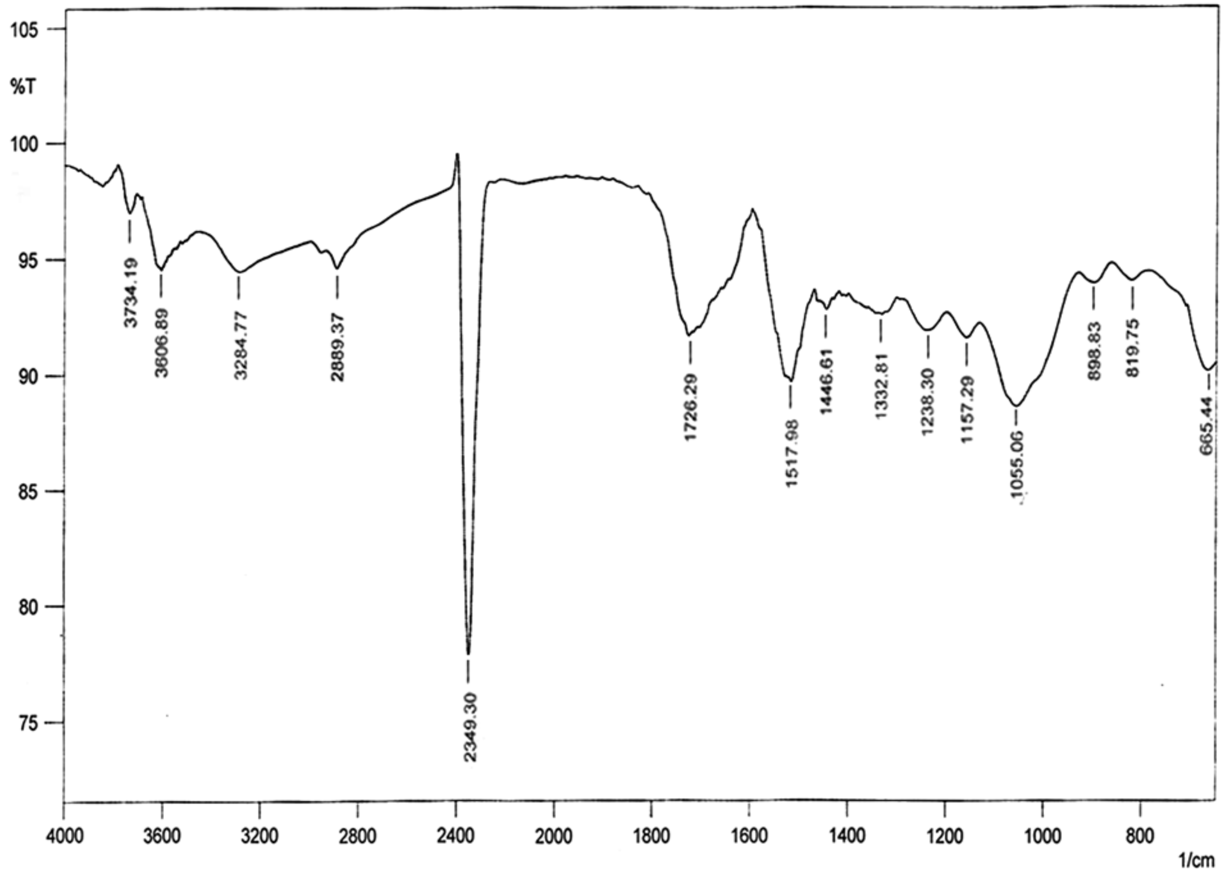

Fig. 1. FTIR spectrum of *Sorghum bicolor* L. biomass.

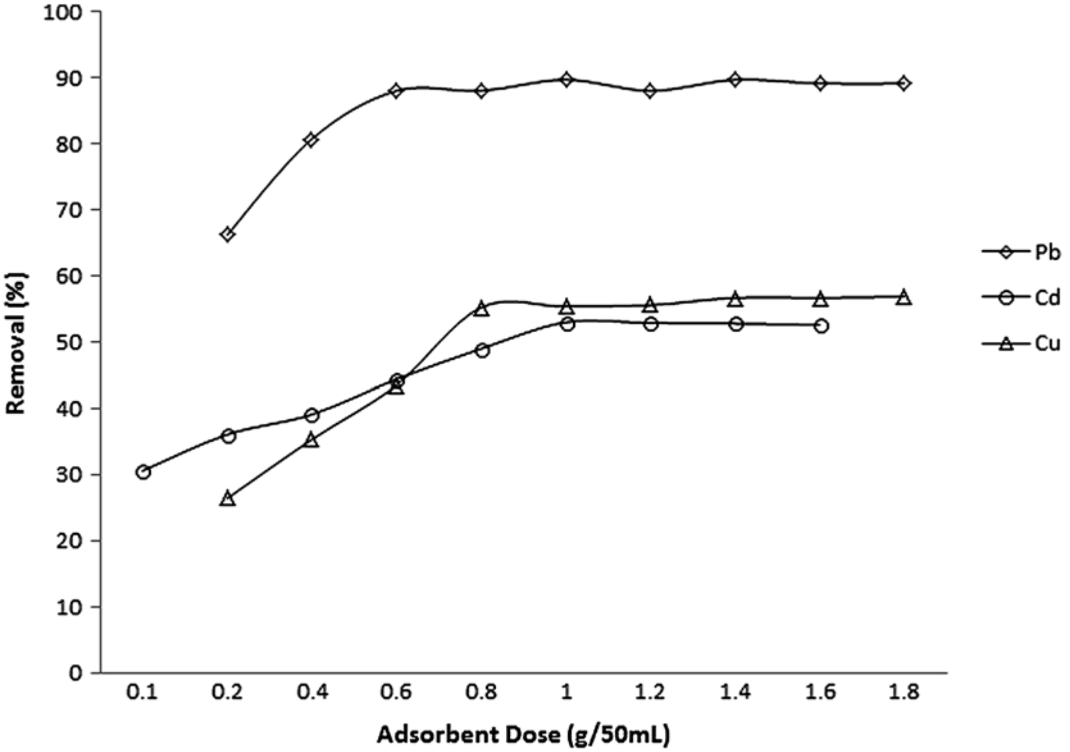

Fig. 2. Influence of adsorbent dosage on Pb(II), Cd(II), and Cu(II) removal. Solution concentration (50 mg/L); contact time (30 min); agitation speed (125 rpm); and temperature (298 K).

highly protonated adsorbent. The maximum removal efficiencies of 89.84, 85.46, and 75.12% were obtained for Pb(II), Cd(II), and Cu(II), respectively, at pH range 5–6. Almost similar results of optimum pH for Pb(II), Cd(II), and Cu(II) binding for various adsorbents have been reported [4,20,21].

Experiments were also conducted to check the effect of agitation speed on adsorption of metal ions and shown in Fig. 4. Agitation speed of 150 rpm was found to be optimum for Pb(II) and Cu(II) and 125 rpm for Cd(II). The reason lies in the fact that at very slow agitation speed, the adsorbent aggregates at the bottom, which results in the unavailability of adsorption sites. Also, at very high speed, centrifugal forces overcomes the ion-dipole forces (physiosorption) resulting in desorption of the adsorbate.

3.4. Adsorption isotherms

An important feature of modern engineering is the ability to satisfactorily model the behavior of the system before committing to industrial scale investment. Conceptual understanding, experimental observations, and measurements of a system are required to develop a good model [22]. Proper analysis and design of adsorption system require appropriate adsorption equilibrium as one of the critical information. Equilibrium concentrations of adsorbate and adsorbent are a function of temperature. Thus, the adsorption–equilibrium relationship at a given temperature is referred to as an adsorption isotherm. Several adsorption isotherms are available and readily adopted to correlate adsorption equilibrium. In the present study, Langmuir (Eq. (1)), Freundlich (Eq. (2)), Temkin (Eq. (3)), and D–R (Dubinin–Radushkevich) (Eq. (4)) isotherm models were used to explain the phenomenon.

$$q_e = \frac{b \times q_m \times C_e}{1 + b \times C_e} \tag{1}$$

$$q_e = K_F \times C_e^{1/n} \tag{2}$$

$$q_e = B_T \times \ln K_T \times C_e \tag{3}$$

$$q_e = q_m \times \exp(-\beta\varepsilon^2) \tag{4}$$

$$R_L = \frac{1}{1 + b \times C_e} \tag{5}$$

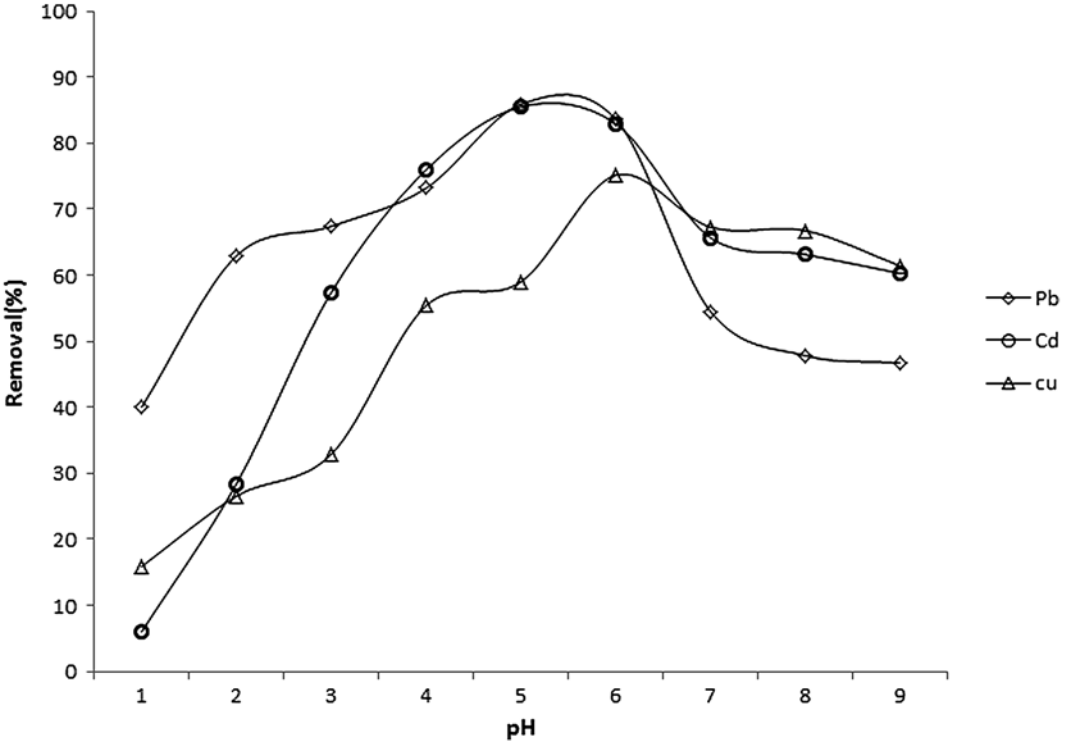

Fig. 3. Influence of pH on Pb(II), Cd(II), and Cu(II) removal. Solution concentration (50 mg/L); adsorbent dosage (1 g/50 mL for Pb(II) and Cd(II), 0.8 g/50 mL for Cu); contact time (30 min); agitation speed (125 rpm); and temperature (298 K).

The Langmuir model presumes uniform energies of adsorption onto the surface and no transmigration of adsorbate in the plane of the surface. Table 1 contains slope and intercept for linear Langmuir plot to calculate q_m (mg/g), the maximum adsorption capacity, and b (L/mg), a constant related to the free energy of adsorption. As given in Table 1, the Langmuir equation represented the adsorption process very well. The coefficient of determination (R^2) having values of 0.991, 0.987, and 0.976 for lead, cadmium, and copper, respectively, implies a good mathematical fit. This indicates the homogenous distribution of active sites on the surface of *sorghum* biomass. The maximum adsorption capacity as calculated from the said model was 6.289, 7.87, and 4.34 mg of Pb(II), Cd(II), and Cu(II) per gram of sorghum biomass, respectively. The factor b was used to find out a dimensionless constant called separation factor or equilibrium parameter, R_L (Eq. (5)). The value of R_L points out the favorability of the process: $R_L > 1$ means unfavorable, $R_L = 1$ signifies linear, $R_L = 0–1$ entails favorable, and $R_L < 0$ implies irreversible [11,16]. In the present case, values were in the range 0.416–0.165 that meant favorability of the process and Langmuir isotherm for its proper depiction.

In the next step, the equilibrium data were analyzed with Freundlich model using the linear form of Eq. (2). The slope and intercept of Freundlich model are given in Table 1 from which, the constant indicative of relative adsorption capacity (K_F) and factor indicative of adsorption intensity (n) were calculated. The magnitude of the factor n is an indication of the favorability of adsorption. Values of n in the range 2–10 represent better, 1–2 good, and less than one average adsorption characteristics [16,23]. In the present study, the magnitude of the factor n was found 1.428 for Pb(II), 1.295 for Cd(II), and 1.901 for Cu(II), all represents the good adsorption characteristics. The coefficient of determination (R^2) was approaching to one (Table 1), pointing out the good fit of Freundlich model. The Freundlich expression is an exponential equation that assumes the increase in concentration of adsorbate on the adsorbent surface with increasing adsorbate concentration in the solution.

The Temkin isotherm is based on the supposition that the decline of the heat of sorption as a function of temperature is linear rather than logarithmic, as entailed in the Freundlich equation. Table 1 illustrates the slope and intercept of the Temkin isotherm equation. The coefficient of determination in this case was

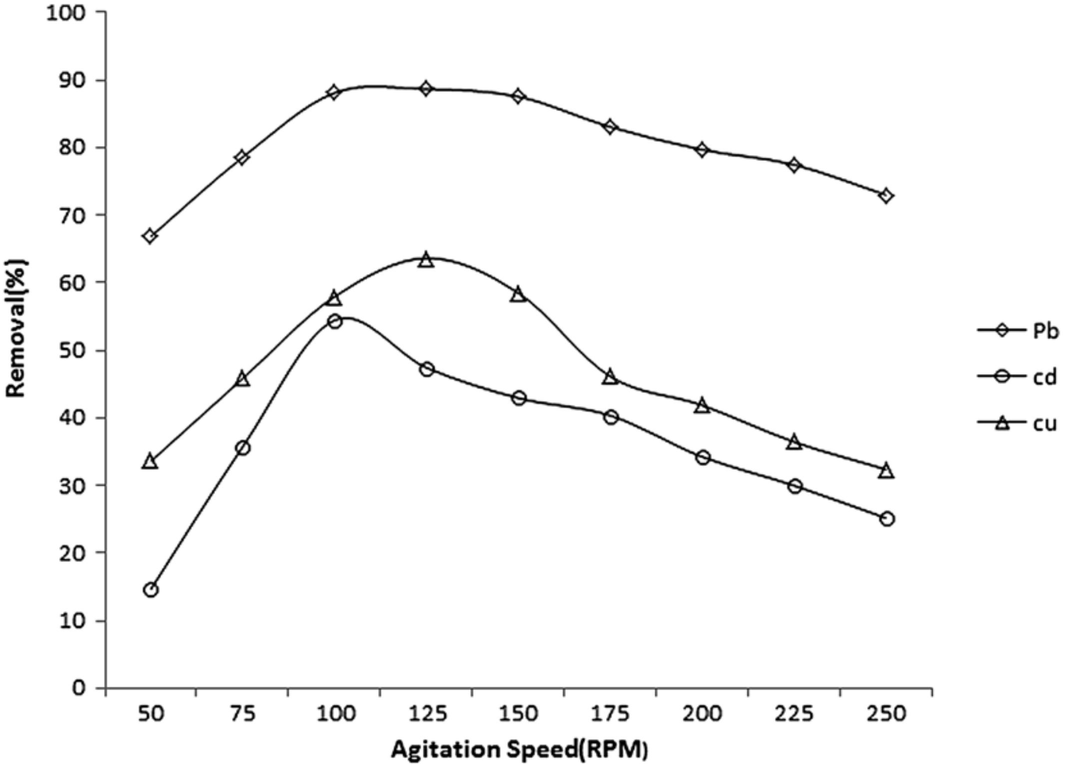

Fig. 4. Influence of agitation speed on Pb(II), Cd(II), and Cu(II) removal. Solution concentration (50 mg/L); adsorbent dosage (1 g/50 mL for Pb(II) and Cd(II), 0.8 g/50 mL for Cu); contact time (30 min); and temperature (298 K).

lower in comparison to that of previous two models, pointing out the inferior fitness of the Temkin model for the present study. The value 0.992 for Pb(II), 1.418 For Cd(II), and 0.495 for Cu(II), all less than eight depicts that there is weak interaction forces present in between the adsorbent and adsorbate i.e. the process would be physiosorption [24].

The nature of the adsorption (physiosorption or chemiosorption) was determined by using D–R model. The values of D–R parameters q_m, β, E, and R^2 for Pb (II), Cd(II), and Cu(II) obtained from the of Eq. (4) are tabulated in the Table 1. E values (kJ/mol) less than eight imply the presence of physical and van der Waal's forces indicating physiosorption. Values in between 8 and 16 indicate ion-exchange mechanism, whereas $E > 16$ depicts particle diffusion [25]. The E values for Pb(II), Cd(II), and Cu(II) under study described physiosorption as the operating phenomenon.

Nonlinear isotherm plots for Pb(II), Cd(II), and Cu (II) are also studied and plotted in Fig. 5(a)–(c), respectively. The figures clearly explain that Langmuir isotherm explains the experimental data clearly. The order of fit in relation to coefficient of determination was Langmuir > Freundlich > D–R > Temkin.

3.5. Effect of contact time—kinetic studies

The adsorption data for the uptake of Pb(II), Cd (II), and Cu(II) vs. contact time at different initial concentration ranging from 25 to 200 mg/L are represented in Fig. 6(a)–(c), respectively. It can be observed that percentage adsorption (Removal%) increased with time and at some point, it reached a constant value where no more metal was adsorbed from the solution. At this point, the amount of metallic species being absorbed by the adsorbent was in a state of dynamic equilibrium with the amount of metallic species being desorbed from the adsorbent. The contact time needed for Pb solutions with initial concentration of 25 ppm to reach equilibrium was 15, 25 min for Pb solution with initial concentration of 50 ppm, and for the initial concentration of 100 and 200 ppm, the contact time needed to reach equilibrium was 30 and 40 min, respectively. The contact time needed for Cd solutions with initial concentration of 25 ppm to reach equilibrium was 15 min, 25 min for Pb solution with initial concentration of 50 ppm, and for the initial concentration of 100 and 200 ppm, the contact time needed to reach equilibrium was 30 and 40 min, respectively. The contact time needed for Cu solutions with initial concentration of 25 ppm to reach equilibrium was

Table 1
Adsorption isotherm parameters

Langmuir isotherm parameters

Metals	Slope	Intercept	R^2	q_m (mg/g)	b (L/mg)	R_L
Lead	3.339	0.159	0.991	6.289	0.047	0.298
Cadmium	4.542	0.127	0.987	7.87	0.028	0.416
Copper	2.221	0.230	0.976	4.34	0.101	0.165

Freundlich isotherm parameters

Metals	Slope	Intercept	R^2	n	K_F
Lead	0.7	−0.412	0.988	1.428571	0.387258
Cadmium	0.772	−0.551	0.988	1.295337	0.28119
Copper	0.526	−0.22	0.986	1.901141	0.60256

Temkin isotherm parameters

Metals	Slope	Intercept	R^2	B_T (kJ/mol)	K_T
Lead	1.367	−0.992	0.970	0.992	1.367
Cadmium	1.454	−1.481	0.959	1.481	1.454
Copper	1.177	−0.495	0.928	0.495	1.177

D–R isotherm parameter

Metals	Slope	Intercept	R^2	E (kJ/mol)	q_m(mg/g)
Lead	−0.002	1.319	0.943	15.81139	3.73968
Cadmium	−0.003	1.412	0.942	12.90994	4.104156
Copper	−0.002	1.335	0.899	15.81139	3.799996

15 min, 20 min for Cu solution with initial concentration of 50 ppm, and for the initial concentration of 100 and 200 ppm, the contact time needed to reach equilibrium was 30 and 35 min, respectively.

This is due to the fact that adsorption sites took up the available metal ions more quickly at lower concentrations, but metal needed to diffuse to the inner sites of the sorbent for higher concentrations. The kinetic

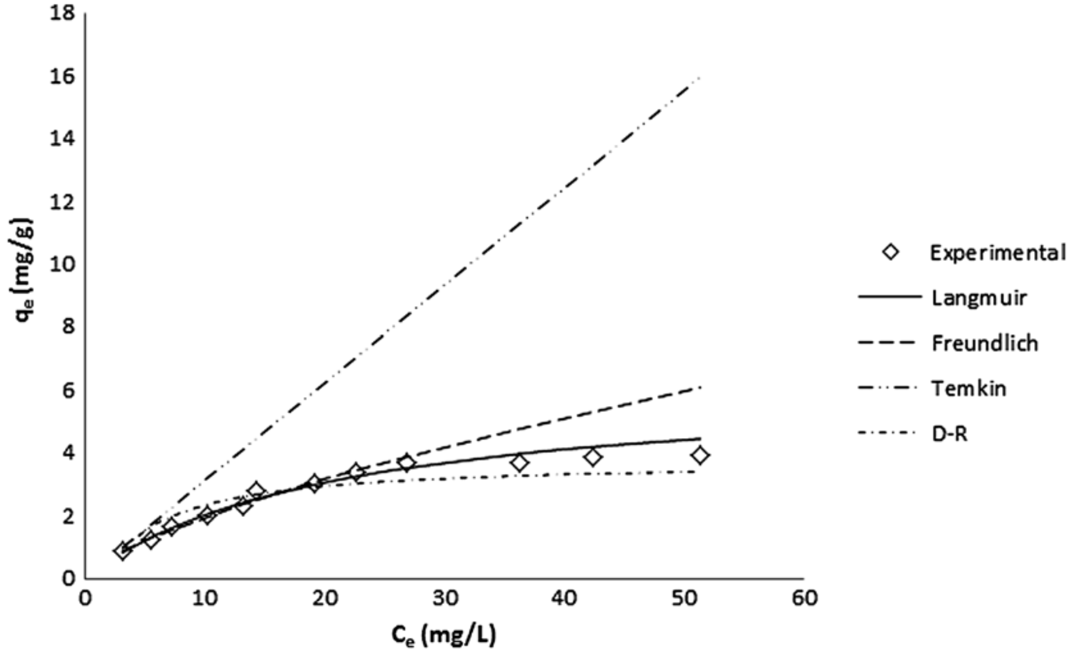

Fig. 5(a). Nonlinear isotherms plot for Pb(II) adsorption on *Sorghum bicolor* L. Initial concentration (20–130 mg/L); adsorbent dosage (1.0 g/50 mL).

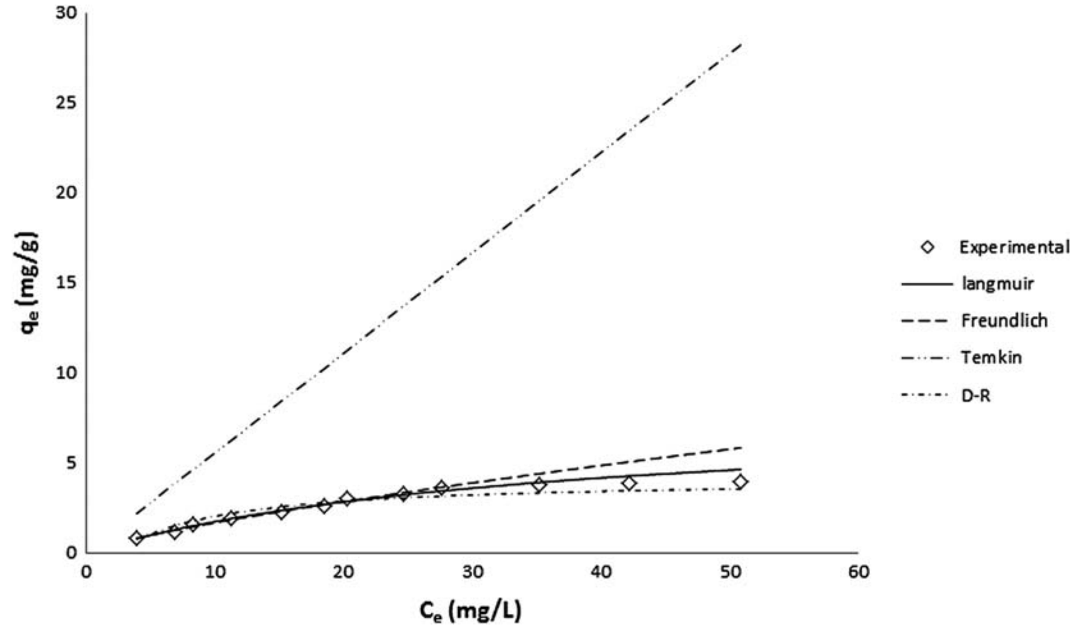

Fig. 5(b). Nonlinear isotherms plot for Cd(II) adsorption on *Sorghum bicolor* L. Initial concentration (20–130 mg/L); adsorbent dosage (1.0 g/50 mL).

results also showed that the sorption process was uniform with time and can be considered very fast.

The mechanisms of adsorption processes such as mass transfer and chemical reaction was examined by using pseudo-first-order (Lagergren) and pseudo-second-order kinetic models.

The linear equation of the pseudo-first-order model is given as:

$$\frac{1}{q_t} = \frac{1}{q_e} + \frac{k_1}{q_e \times t} \tag{6}$$

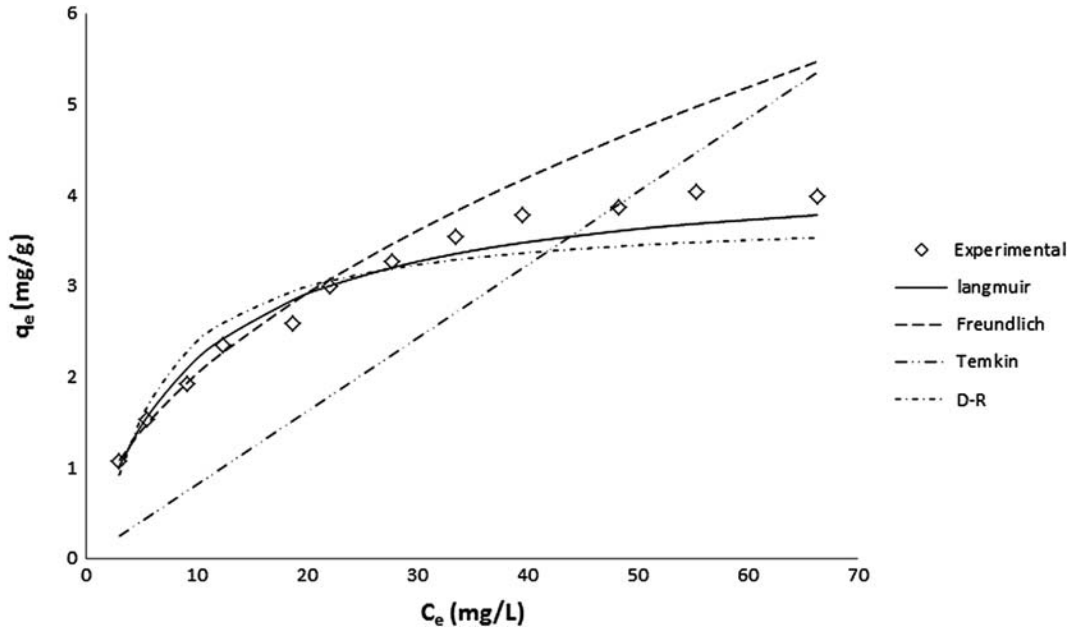

Fig. 5(c). Nonlinear isotherms plot for Cu(II) adsorption on *Sorghum bicolor* L. Initial concentration (20–130 mg/L); adsorbent dosage (0.8 g/50 mL).

Table 2
Kinetic parameters

Metal ions	Pseudo-first-order kinetics			q_e (mg/g) (Experimental)	Pseudo-second-order kinetics		
	k_1 (min^{-1})	R^2	q_e (mg/g)		k_2 (min^{-1})	R^2	q_e (mg/g)
Lead	0.157	0.891	0.446	2.202	24.5	0.999	2.227
Cadmium	0.155	0.962	1.565	2.120	4.914	0.998	2.252
Copper	0.144	0.945	1.239	2.174	−18.9	0.986	1.960

where, q_e and q_t (mg/g) refer to the amount of metals adsorbed on sorghum biomass at equilibrium and t (min), respectively; k_1 represents the first-order rate constant (min^{-1}). Table 2 illustrates the data calculated from the pseudo-first-order kinetic model.

Equation describing the pseudo-second-order model is given by the linear equation:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \tag{7}$$

where, k_2 is the second-order rate constant. The kinetic data calculated from the above Eq. (5) is tabulated in Table 2.

The observed R^2 values for the pseudo-first-order (less than 0.97) and pseudo-second-order (greater than 0.98) clearly showed a perfect fit for pseudo-second-order model as compared to pseudo-first-order model. In addition, the *qe* values calculated from pseudo-second-order model was in close accordance to the experimental values for Pb(II), Cd(II), and Cu(II). So, the conclusion can be made that the adsorption mechanism was governed by pseudo-second-order kinetic model. Several studies showed that the adsorption of divalent metal ions on various adsorbents mostly followed pseudo-second-order kinetic model [26–28].

3.6. Effect of temperature—thermodynamic parameters

Temperature is an important parameter which affects the adsorption process. Fig. 7 shows the influence of temperature on the adsorption, showing increased adsorption capacity with temperature. Increased metal removal at high temperature

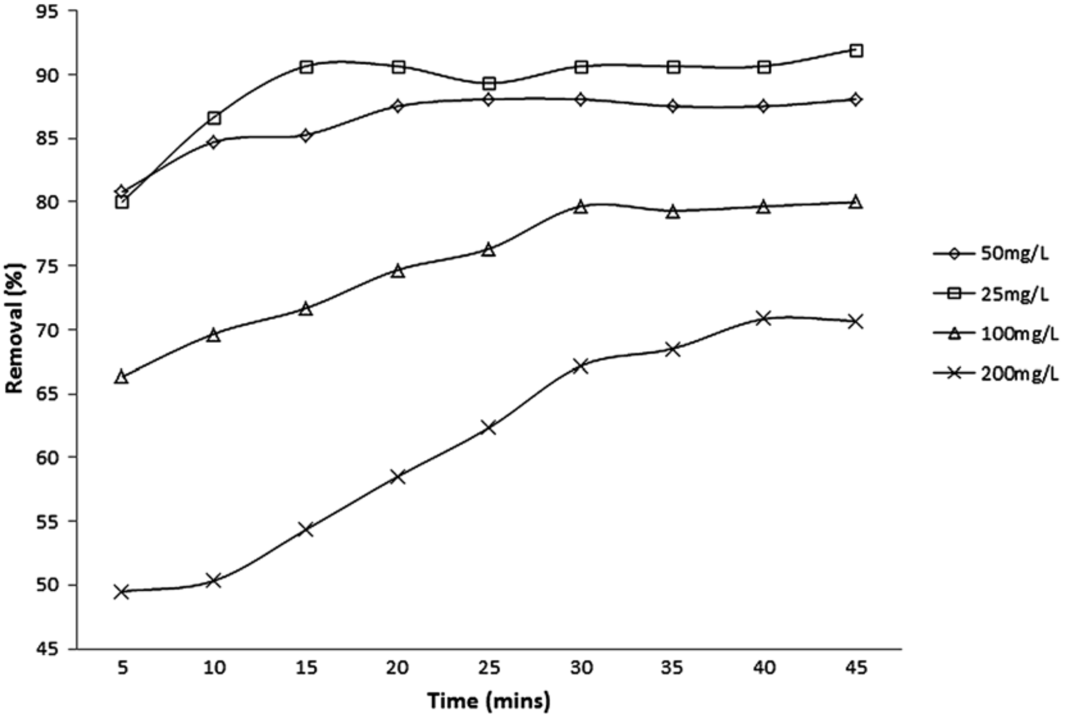

Fig. 6(a). Influence of contact time on Pb(II) removal. Solution concentration (25–200 mg/L); adsorbent dosage (1 g/50 mL); and temperature (298 K).

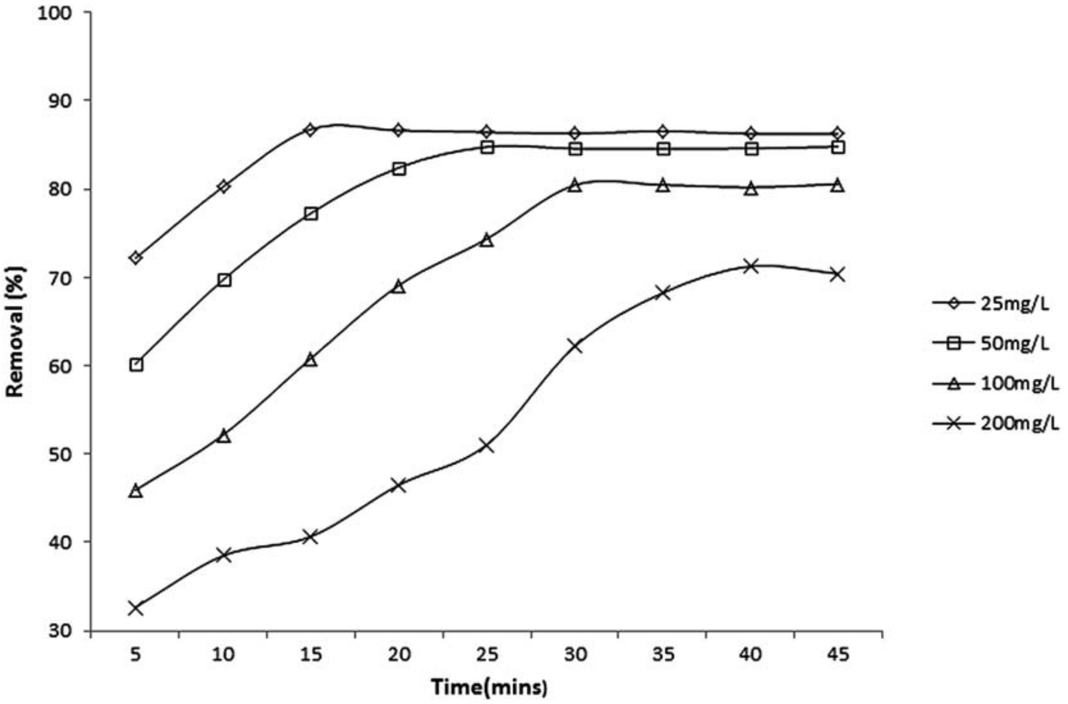

Fig. 6(b). Influence of contact time on Cd(II) removal. Solution concentration (25–200 mg/L); adsorbent dosage (1 g/50 mL); and temperature (298 K).

indicated the adsorption process to be endothermic in nature. The observed trend suggested that sorghum biomass can effectively be used for the removal of metals from aqueous solution at high temperatures.

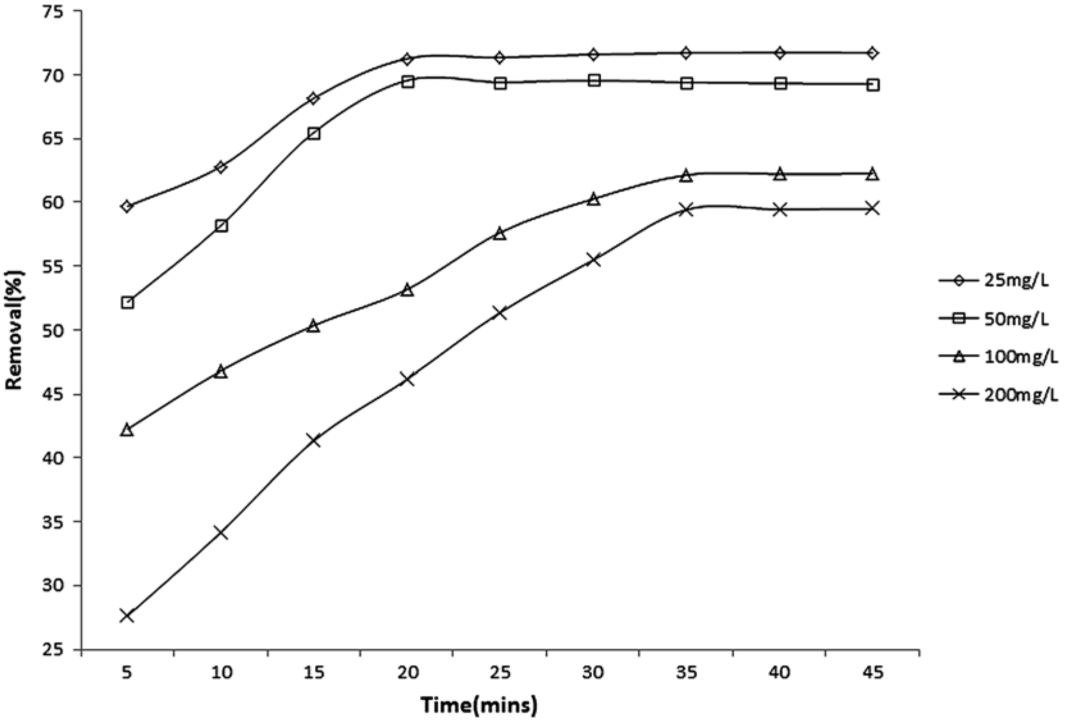

Fig. 6(c). Influence of contact time on Cu(II) removal. Solution concentration (25–200 mg/L); adsorbent dosage (1 g/50 mL); and temperature (298 K).

Eqs. (8–10) were used to calculate the thermodynamic parameters such as changes in standard free energy (ΔG°), enthalpy (ΔH°) and entropy (ΔS°). The calculated parameters depict the nature of the process.

$$\Delta G^\circ = -RT \ln K_D \tag{8}$$

$$\ln K_D = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \tag{9}$$

where, R is the universal gas constant ($8.3134\,\mathrm{J\,mol^{-1}\,K^{-1}}$), T is the temperature of the medium (K), and K_D is the distribution coefficient, obtained from equation:

$$K_D = \frac{C_o - C_e}{C_e} \tag{10}$$

where, q_e is the equilibrium amount of metal adsorbed (mg/g) and C_e is the concentration of metal in solution at equilibrium (mg/L) [29,30]. Thermodynamic parameters calculated using above equations is given in Table 3. The negative values of ΔG° for the adsorption of Pb(II), Cd(II), and Cu(II) by sorghum biomass at the studied temperature range affirmed the feasibility of the process and suggest that the process would be a spontaneous one. In addition, the decrease of ΔG° values with the increase in temperature represents that the adsorption process was endothermic in

Table 3
Thermodynamic parameters

Metal ions	Temperature (K)	ΔG^o	ΔH^o	ΔS^o
Pb(II)	283.16	−49.5388	213.8	0.93
	293.16	−58.8388		
	303.16	−68.1388		
	313.16	−77.4388		
	323.16	−86.7388		
Cd(II)	283.16	−5.9464	571.7	2.04
	293.16	−26.3464		
	303.16	−46.7464		
	313.16	−67.1464		
	323.16	−87.5464		
Cu(II)	283.16	−1.75356	264.7	0.941
	293.16	−10.2694		
	303.16	−20.1094		
	313.16	−29.9494		

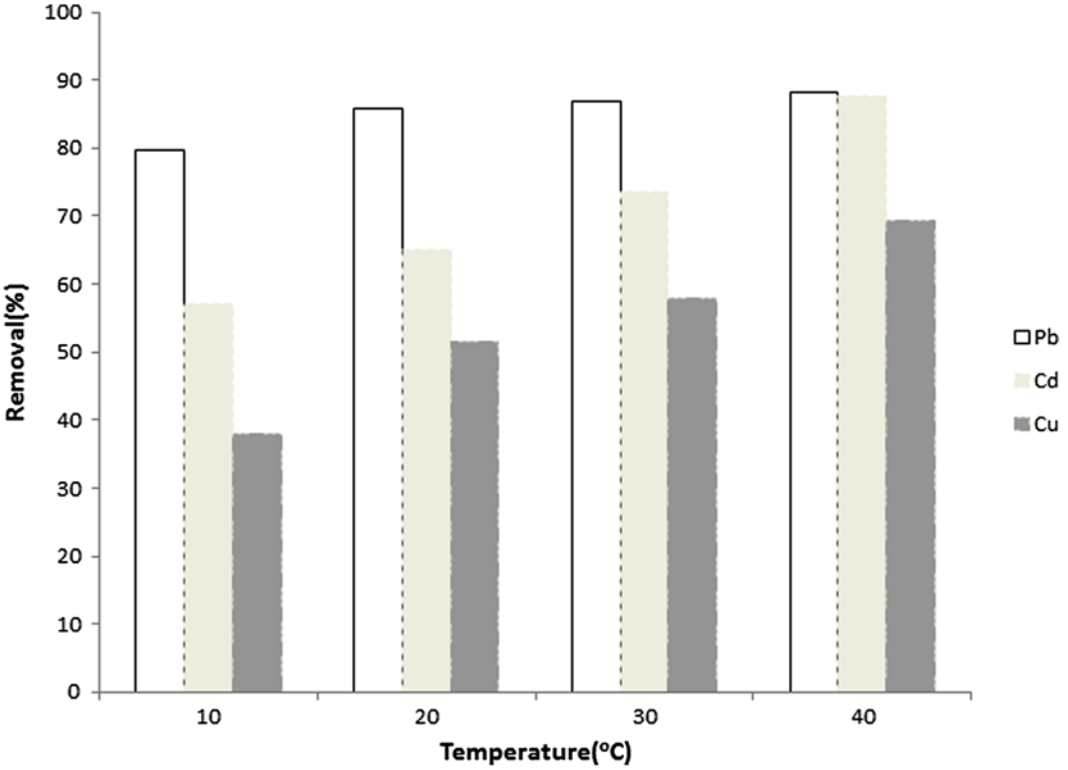

Fig. 7. Influence of temperature on Pb(II), Cd(II) and Cu(II) removal. Solution concentration (50 mg/L); adsorbent dosage (1 g/50 mL for Pb(II) and Cd(II), 0.8 g/50 mL for Cu); and contact time (30 min).

nature. The calculated value of ΔH° also corroborated this statement. Positive values of ΔS° showed the increased randomness at the solid–solution interface during the adsorption of Pb(II), Cd(II), and Cu(II) [31].

4. Conclusion

Sorghum bicolor L.; a waste agro-product, showed an effective removal of toxic metal ions (Pb(II), Cd(II), and Cu(II)) form aqueous systems. The calculated optimum process parameters showed that an effective removal of the said metal ions can be occurred in slightly acidic environment (pH 5–6). The equilibrium study showed an appreciable uptake capacity of the adsorbent, i.e. 6.289, 7.87, and 4.34 mg of Pb(II), Cd(II), and Cu(II) per g of sorghum biomass, respectively. The adsorption mechanism was governed by the pseudo-second-order kinetic model. Thermodynamic parameters indicated that the process was energetically feasible and endothermic in nature. So, *Sorghum bicolor* L. proved to be an effective, low-cost and eco-friendly adsorbent for the removal of toxic metal ions form aqueous systems. Another positive feature, found during the study, was that there exist weak interactive forces between adsorbent and adsorbate which leads to the idea of adsorbent regeneration.

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