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Removal of Pb(II) ions from aqueous solutions using *Bombax ceiba* saw dust activated carbon

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ABSTRACT

The isotherms, kinetics and thermodynamics of Pb(II) ions from aqueous solution by activated carbon prepared from *Bombax ceiba* sawdust (SDC) were carried out in a batch adsorption system. The effects of pH, adsorbent dosage, contact time, initial concentration of Pb(II) and temperature on the adsorption were studied. Maximum adsorption of Pb(II) occurred at pH 5. Pseudo first order, pseudo second order and intraparticle diffusion models were applied to kinetic data. The sorptive mechanism followed the pseudo second-order kinetics and intra particle diffusion model. The equilibration data fitted well with both Langmuir and Freundlich isotherm model with maximum sorption capacity of 209 mg g^{-1}. The mean free energy of adsorption calculated from Dubinin–Radushkevich (D-R) isotherm model indicated that the adsorption of metal ions was found to be by chemical ion exchange. Thermodynamic parameters and Tempkin constant showed that the sorption process of Pb(II) onto SDC was feasible, spontaneous and endothermic under studied conditions.

Keywords: Adsorption; Isotherms; Kinetics; Pb(II); Saw dust carbon; Thermodynamics

1. Introduction

Heavy metals are major pollutants in marine, ground and industrial wastewaters. Lead is attracting wide attention of environmentalists as one of the most toxic heavy metals. The major sources of lead released into the environment by waste streams are storage batteries; lead smelting, mining, plating, ammunition, ceramic and glass industries [1]. The permissible limit of lead in drinking water is 0.05 mg L^{-1} [2]. The presence of lead in drinking water above the permissible limit can result in delays in physical and mental development, along with slight deficits in attention span and learning abilities in babies and children. In adults, it can cause blood pressure [3]. Removal of toxic Pb(II) ions from wastewaters before being discharged into the sewage system or into the aquatic environment is considered essential and the need of the hour.

Research has been carried out for developing cost effective heavy metal removal techniques. Physicochemical methods, such as chemical precipitation, chemical oxidation or reduction, filtration, electrochemical treatment, application of membrane technology, solvent extraction and ion exchange process have been traditionally employed for the heavy metal removal from industrial waste water [4]. The adsorption method is preferred to other methods in view of its efficiency and the ease with which it can apply in the treatment of wastewater containing heavy metals.

Recently agricultural materials such as waste wool, nut wastes, tree barks, modified cotton and sawdust have

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been used to remove heavy metals from wastewater. Most of the agricultural byproducts are not having any commercial value which is largely discarded in agricultural sector. Agricultural wastes such as bark and saw dust, which are in large quantities in timber mills, often present a disposal problem. Several researchers have reported the use of sawdust and modified sawdust for the removal of heavy metals from aqueous solutions [5–15].

The present study is to evaluate and observe the adsorption capacity of chemically activated *Bombax ceiba* sawdust carbon for Pb(II) ion removal from aqueous solution. This sawdust is a by-product of wood industry waste and available in large quantities. Further more no reports are available on the use of this material for the treatment of Pb(II) ion from aqueous stream. The batch adsorption technique reported here are of the influence of temperature on the rate constant for the removal of Pb(II) ion. The activation parameters calculated from the adsorption measurements in the present work, are to be very useful in elucidating the nature of adsorption for environmental engineers.

2. Materials and methods

2.1. Chemicals

All the chemicals used in this study were of analytical grade obtained from Ranbaxy, Qualigens and S.D Fine Chemicals Ltd, India. Stock solution of lead was prepared using lead nitrate in double distilled water. Pb(II) solutions of different concentrations were obtained by diluting the stock solution. Standard acid and base solutions (0.1 M HCl and 0.1 M NaOH) were used for pH adjustments.

2.2. Equipment

pH measurements were made using a pH meter (model Elico-LI-120). The concentration of lead solutions was analyzed using a UV-visible spectrophotometer (model – Genesis 2). A temperature controlled mechanical shaker (model – TECHNO) was used for agitating the solutions. Carbon, hydrohen, nitrogen, sulphurs and oxygen content of the activated carbon was analyzed by elemental analyzer model Vario EL III (Vario EL, Elemental Analyzer system, Germany).

2.3. Preparation of *Bombax ceiba* saw dust activated carbon

Sawdust of *Bombax ceiba* plant was collected from wood industries in Coimbatore, India and washed with deionized water four to five times for removing dirt and earthy impurities. The washed saw dusts were dried at 90°C for 10 h. The dried saw dusts were used for carbon preparation by mixing with concentrated sulphuric acid in the ratio of 1:1 and then it was kept at 150°C for 12 h. This carbonized material was washed with distilled water several times to remove the free acid and soaked in 5% sodium bicarbonate solution to remove any residual acid. This material was then again washed with distilled water and dried at 105°C in a hot air oven for 10 h and then sieved into different particle sizes ranges from 90 to 600 μm. The material was placed in airtight container for further studies.

2.4. Characterization of adsorbent

The physico-chemical characteristics of *Bombax ceiba* saw dust activated carbon was characterized by means of pH, ash content, decolorizing power, water-soluble matter, acid soluble matter, as per standard procedures [16]. The Zero point charge of the adsorbent was determined by the solid addition method [17]. The surface area of the adsorbent was determined by acetic acid adsorption method [18]. The physico-chemical properties along with the percentage of carbon, hydrogen, nitrogen and sulphur in the activated carbon made from sawdust of *Bombax ceiba* were presented in Table 1.

2.5. Batch adsorption experiments

The kinetics of adsorption of Pb(II) ions on the SDC was carried out using 10 to 50 mg L^{-1} initial concentration of the metal ions. 50 mL of Pb(II) solution of required concentration were adjusted to desired pH and taken in 100 mL reaction bottle for adsorption studies. Different dosages of the adsorbent were added into this solution and agitated for a predetermined period in a mechanical shaker. The adsorbents were separated by centrifugation

Table 1
Characteristic properties of activated carbon.

Parameter	Value
pH (1%solution)	7.2
Moisture (%)	5.75
Ash (%)	2.11
Surface area ($m^2\,g^{-1}$)	369.4
Decolorizing power (mg g^{-1})	15.0
Bulk density (g L^{-1})	0.740
Water-soluble matter (%)	1.76
Acid-soluble matter 0.25 M HCl (%)	4.01
pH_{ZPC}	5.2
Carbon (%)	48.01
Hydrogen (%)	3.869
Nitrogen (%)	0.124
Sulphur (%)	2.243
Oxygen (%)	45.754

and the supernatant was analyzed for the residual Pb(II) concentration spectrophotometrically at a wavelength of 520 nm using PAR reagent (2,4-Pyridyl azo resorcinol) [19] as a complexing agent. The same method was used in the subsequent experiments.

Langmuir adsorption isotherm and kinetic studies were carried out with different initial concentrations of Pb(II) from 10 to 50 mg L^{-1} at constant adsorbent dosages of 0.2 g L^{-1}. Freundlich adsorption isotherm studies were carried out with different adsorbent dosages from 0.1 to 0.8 g L^{-1} for different initial concentration of Pb(II). The effects of pH and particle size were studied by employing 10 and 30 mg L^{-1} of the Pb(II) solutions and an adsorbent dosage of 0.2 g L^{-1}. Temperature effect was studied with a concentration of 50 mg L^{-1} of the adsorbate and an adsorbent dose of 0.2 g L^{-1} at temperatures 30°C, 40°C and 50°C. In order to correct for any adsorption of Pb(II) on the container surface, control experiments were carried out without adsorbent. It was found that no adsorption occurred by the container walls. In addition, all mixing vessels were kept sealed throughout the duration of each isotherm test to minimize dissolution of gaseous species in the atmosphere.

3. Results and discussions

3.1. Effect of pH

One of the most important factors affecting sorption of metal ions is the pH of the solution [20]. The pH of the solution affects the charge on the surface of the adsorbents, so the change in pH affects the adsorption process. This is due to two factors (i) H^+ are competing with metal ions for adsorption. (ii) Solution pH influences the ionization of functional groups on the adsorbent surfaces and chemical speciation of metal ions. The influence of pH on the sorption of Pb(II) onto sawdust was studied by varying the pH of Pb(II) solution from 2 to 6 and the results were shown in Fig. 1. The maximum sorption was found to be at pH 5.0. So all the experiments were carried out at pH 5.0. The removal of Pb(II) by sawdust adsorption increased with increasing pH from 2.0 to 5.0. A slight decrease in the adsorption was observed above pH 5 and at pH 6 Pb(II) started precipitating as $Pb(OH)_2$ and hence pH experiments at alkaline ranges were restricted. Similar results were reported by Yu *et al.* [21], Ayyappan *et al.* [22] and Jayaram *et al.* [23] for adsorption of Pb(II).

At lower pH, the H^+ ions compete with metal cations for the exchange sites on the SDC. The perusal of Pb(II) speciation diagram indicates that the dominant species of adsorption are Pb^{2+} and $PbOH^+$ at pH less than six and $Pb(OH)_2$ at pH greater than six. [8]. It was observed that at low pH the adsorption was very low. This can be explained that at low pH values the H^+ ion concentration is high and therefore protons compete with lead ions for surface sites, because at low pH the lead are present as Pb^{2+} ions. When the pH is increased deprotonation of the surface functional groups of the adsorbent results a decrease in the surface positive charge [24]. As a consequence the electrostatic repulsion between the positively charged metal ions and the surface is lowered favoring adsorption.

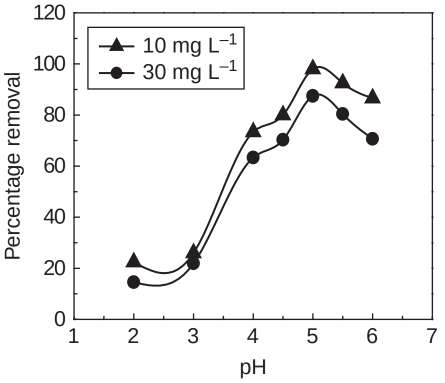

Fig. 1. Effect of pH on the sorption of Pb(II) onto SDC (metal ion concentration =10 and 30 mg L^{-1}; adsorbent dose = 0.2 g L^{-1}; contact time = 120 min; temperature = 303 K).

The cell walls of sawdust mainly consist of cellulose, lignin and many hydroxyl groups, such as tannins or other phenolic compounds. All these components are active ion exchange compounds. Based on the electron donating nature of the O, S, N containing groups in sawdust materials and the e^- accepting nature of Pb(II) ion, the ion exchange mechanism is proposed. The ion exchange mechanism is shown in the following equations [25]:

$$2\text{R-COH} + \text{M}^{2+} \leftrightarrow (\text{R-CO})_2\text{M} + 2\text{H}^+$$
$$\text{R-COH} + \text{MOH}^+ \leftrightarrow \text{RCOMOH} + \text{H}^+,$$

where R is the matrix of sawdust.

3.2. Adsorption isotherms

3.2.1. Langmuir isotherm

The adsorption data has been analyzed in the light of Langmuir and Freundlich adsorption models. The Langmuir equation may be described as [26]

$$C_e/q_e = 1/Q_o b + C_e/Q_o, \qquad (1)$$

where C_e is the equilibrium concentration of metal (mg L^{-1}), Q_o and b are Langmuir constants relating to adsorption capacity and adsorption energy respectively. The Langmuir adsorption isotherm is valid for

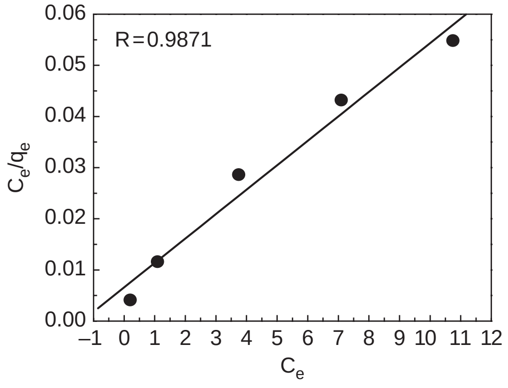

Fig. 2. Langmuir isotherm plot for the adsorption of Pb(II) onto SDC (adsorbent dose = 0.2 g L^{-1}; contact time = 120 min; pH = 5; temperature = 303 K).

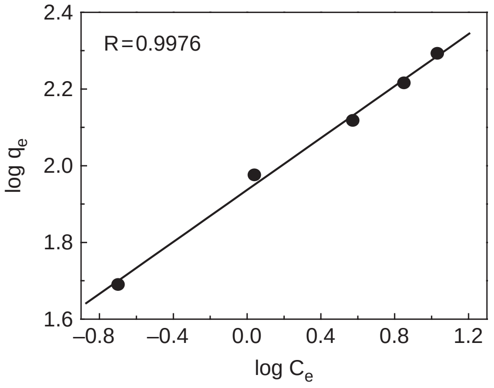

Fig. 3. Freundlich isotherm plot for the sorption of Pb(II) onto SDC (adsorbent dose = 0.2 g L^{-1}; contact time = 120 min; pH = 5; temperature = 303 K).

monolayer adsorption onto the surface of the adsorbent containing a finite number of identical sites. The plot of C_e/q_e against C_e gives a straight line (Fig. 2) showing the applicability of Langmuir isotherm. The adsorption capacity Q_o and energy of adsorption b were found to be 209 mg g^{-1} and 0.7253 L g^{-1} The essential features of the Langmuir Isotherm can be expressed in terms of dimensionless constant referred to as separation factor for equilibrium parameter (R_L) which is defined by the following relation [27]:

$$R_L = 1/1 + bC_o, \tag{2}$$

where C_o is the initial metal ion concentration (mg L^{-1}). As the R_L values lies between 0 and 1, the adsorption process is favorable. Further, the calculated R_L values are 0.121, 0.065, 0.044, 0.033 and 0.027 for the initial concentrations 10 to 50 mg L^{-1} respectively. Therefore sorption was favorable.

The adsorption capacity of other saw dusts for Pb(II) obtained by few other researchers are: (i) 22.22 mg g^{-1} for saw dust of pinus sylvestris [28]; (ii) 124.5 mg g^{-1} for chemically modified saw dust [8]; (iii) 21.05 mg g^{-1} for sawdust of poplar tree [29]; (iv) 34.246 mg g^{-1} for meranti sawdust [30]. A comparison of these values with the one obtained in this study (209 mg g^{-1}) showed that saw dust of *Bombax ceiba* used in this work exhibited a reasonable capacity for Pb(II) adsorption from aqueous solution.

3.2.2. Freundlich isotherm

The Freundlich isotherm, which is an empirical model used to describe adsorption in aqueous systems is shown as [31]

$$\log q_e = \log k_F + 1/n \log C_e, \tag{3}$$

where k_F and n are constants related to adsorption capacity and the adsorption intensity, respectively. The plot of $\log q_e$ against $\log C_e$ (Fig. 3) for different initial metal ion concentrations was found to be linear indicating the applicability of the Freundlich model. The intercept of the line is roughly an indicator of the adsorption capacity, and the slope is the indication of adsorption intensity. Adsorption of Pb(II) onto SDC fitted both the Langmuir and Freundlich isotherms.

3.2.3. Dubinin–Radushkevich (D-R) isotherm model

The equilibrium data were also applied to the D-R isotherm model to determine the nature of adsorption processes as physical or chemical [32]. The linearized form of the the D-R isotherm equation,

$$\ln q_e = \ln q_m - \beta\varepsilon^2, \tag{4}$$

where q_e is the amount of metal ions adsorbed on per unit weight of adsorbent (mol g^{-1}), q_m the theoretical saturation sorption capacity (mol g^{-1}), β is a constant related to mean free energy of sorption per mole of the sorbate (mol^2 J^{-2}), and ε is the Polanyi Potential, which is equal to RT $\ln(1+1/C_e)$, where R is the gas constant ($Jmol^{-1}$ K^{-1}) and T(K) is the absolute temperature. A plot of $\ln q_e$ versus ε^2 should give straight line (Fig 4).

The constant β gives an idea about the mean free energy E (kJ mol^{-1}) of sorption per molecule of the sorbate when it is transferred to the surface of the solid from infinity in the solution and can be calculated using the relationship:

$$E = 1/(2\beta)^{1/2}. \tag{5}$$

This parameter gives information about sorption mechanism as chemical ion exchange or physical sorption. The magnitude of E is between 8 and 16 kJ mol^{-1}, the sorption process follows chemical ion exchange, while for the values of $E < 8$ kJ mol^{-1}, the sorption process is

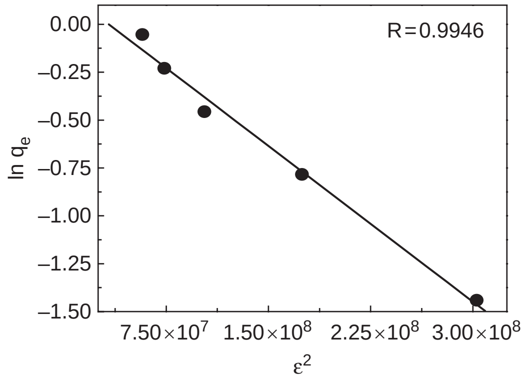

Fig. 4. Dubinin–Redushkevich isotherm plot for the sorption of Pb(II) onto SDC (adsorbent dose = 0.2 g L^{-1}; contact time = 120 min; pH = 5; temperature = 303 K).

of a physical nature. In the present study, the mean free energy of sorption was found to be 9.9 kJ mol^{-1} indicating support to chemical ion exchange mechanism. Similar results were reported by Ahmet Sari *et al*, [33] and Sibel Tunali *et al.*, [34]. The Langmuir, Freundlich and D-R parameters for the adsorption of Pb(II) onto SDC are listed in Table 2.

3.2.4. Tempkin isotherm model

Heat of adsorption and the adsorbate–adsorbate interaction on adsorption isotherms were studied by Tempkin and Pyshev, who suggested that because of these interactions the energy of adsorption of all the molecules decreases linearly with coverage. Tempkin isotherm is given as [35]

$$q_e = B\ln(K_T C_e). \tag{6}$$

It can be expressed in the linear form as

$$q_e = B\ln K_T + B\ln C_e, \tag{7}$$

where B = RT/b, R is the universal gas constant and T is the absolute temperature.

A plot of q_e versus $\ln C_e$ enables the determination of the isotherm constants B and K_T from the slope and the intercept respectively. Tempkin constants are given in Table 5. K_T is the equilibrium binding constant corresponding to the maximum binding energy and the constant B is related to the heat of adsorption. The investigation of adsorption data shows that heat of adsorption increases with increase in temperature, favoring endothermic adsorption [36].

3.3. Adsorption kinetics

The efficiency of the adsorbent was evaluated by studying adsorption kinetics. The rate constant of adsorption is determined from the pseudo-first-order equation of Lagergren [37], which is generally expressed as

$$\mathrm{d}q_t/\mathrm{d}t = k_1(q_e - q_t), \tag{8}$$

where q_e and q_t are the adsorption capacity at equilibrium and at time t, respectively (mg g^{-1}) and k_1 is the rate constant for pseudo-first-order adsorption (min^{-1}). After integration and applying the boundary conditions $t = 0$ to t and $q_t = 0$ to q_e, the integrated form of equation (8) becomes

$$\log(q_e - q_t) = \log q_e - k_1 t/2.303. \tag{9}$$

The slopes and intercepts of plots of $\log(q_e - q_t)$ versus t were used to determine the first-order rate constant k_1 and equilibrium adsorption capacity q_e. In the present study, although the correlation coefficients were reasonably high the model did not predict q_e values equal or even reasonably close, to experimental q_e values (Table. 3). This suggests that the adsorption of Pb(II) onto SDC is not a pseudo-first-order reaction. The pseudo-second-order adsorption kinetic rate equation is expressed as [38]:

$$\mathrm{d}q_t/\mathrm{d}t = k_2(q_e - q_t)^2, \tag{10}$$

where k_2 is the rate constant for pseudo-second-order adsorption g mg^{-1} min^{-1}. For the boundary conditions t = 0 to $t = t$ and $q_t = 0$ to $q_t = q_e$, the integrated form of equation (10) becomes

$$1/(q_e - q_t) = 1/q_e + k_2 t, \tag{11}$$

Table 2
Isotherm constants for Pb(II) ion adsorption onto SDC.

Langmuir		Freundlich		D-R isotherm	
q_e (mg g^{-1})	209.205	K_F (mg g^{-1})	86.50	q_m (mg g^{-1})	247.592
b (L g^{-1})	0.7253	n	2.95	E (kJ mol^{-1})	9.602
R^2	0.9871	R^2	0.9976	R^2	0.9946

(Initial metal ion concentration–10 to 50 mg L^{-1}; pH–5; contact time–120 min; temperature–303 K; adsorbent dose–0.2 g L^{-1}).

Table 3
Comparison of the pseudo-first-order, pseudo-second-order and Intra particle diffusion rate Constants for different Initial Pb(II) concentrations.

Initial concentration (mg L^{-1})	exp q_e (mg g^{-1})	Pseudo first order			Pseudo second order			Intra particle diffusion		
		$K_1 \times 10^{-2}$ (min^{-1})	Cal q_e (mg g^{-1})	R^2	$K_2 \times 10^{-3}$ g mg^{-1} min^{-1}	Cal q_e mg g^{-1}	R^2	K_P mg g^{-1} min$^{1/2}$	q_e mg g^{-1}	R^2
10	49.00	4.339	32.66	0.9612	4.257	50.51	0.9989	2.033	49.64	0.9948
20	94.52	3.109	36.73	0.9974	1.916	98.04	0.9984	4.138	95.19	0.9971
30	131.25	3.961	58.61	0.9942	1.429	136.99	0.9993	5.329	135.31	0.9875
40	164.50	3.132	71.12	0.9717	0.962	169.49	0.9989	6.229	168.64	0.9850
50	196.25	3.017	87.30	0.9959	0.748	204.08	0.9990	8.164	202.04	0.985

(Initial metal ion concentration–10 to 50 mg L^{-1}; pH–5; contact time–120 min; temperature–303 K; adsorbent dose–0.2 g L^{-1}).

which is the integrated rate law for pseudo-second-order reaction. Equation (11) can be rearranged to a linear form

$$t/q_t = 1/k_2 q_e^{\,2} + t/q_e. \tag{12}$$

The slopes and intercepts of plots of t/q_t versus t were used to calculate the q_e and second-order rate constant k_2. The straight lines in plot of t/q_t versus t (Fig. 5) shows a good agreement of experimental data with the second-order kinetic model for different initial metal ion concentrations. The correlation coefficients for this model are greater than 0.995 for all the cases (Table. 3). The best correlation between predicted and experimental q_e values indicates that the adsorption system studied belongs to second-order kinetic model. Further the values of k_2, however, were found to decrease with increase of initial concentration [39]. Increasing the metal ion concentration in solution seems to reduce the diffusion of metal ions in the boundary layer and enhance the diffusion in the solid.

3.4. Intra particle diffusion model

The first- and second-order kinetic models cannot identify the diffusion mechanism and the kinetic results were then analyzed using intra particle diffusion model. The equation can be written as [40]

$$q_t = k_P\, t^{\,1/2} + \mathrm{C}, \tag{13}$$

where C is the intercept and k_p is the intra particle diffusion constant (mg g^{-1} min$^{1/2}$). According to this model, the plot of q_t versus $t^{1/2}$ should be linear if intra particular diffusion is involved in the adsorption process and if these lines pass through the origin the intra particle diffusion is the rate controlling step. In many cases, a linear portion follows an initial steep sloped portion indicating external mass transfer to the intra particle diffusion and plateau to the equilibrium.

This model was applied to the adsorption of Pb(II) on SDC as a function of different initial concentrations of metal ions and the variation of q versus t$^{1/2}$ was given in Fig. 6. The linear portions of the curves did not pass

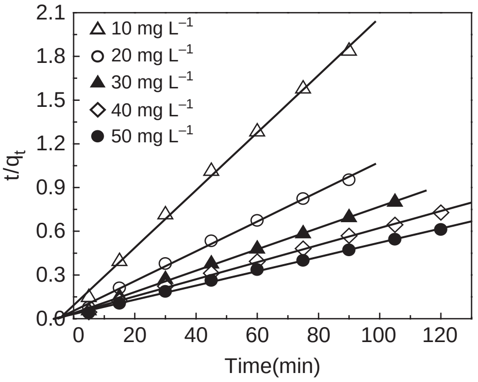

Fig. 5. Pseudo-second order kinetic plots for different initial concentrations (adsorbent dose = 0.2 g L^{-1}; contact time = 120 min; pH = 5; temperature = 303 K).

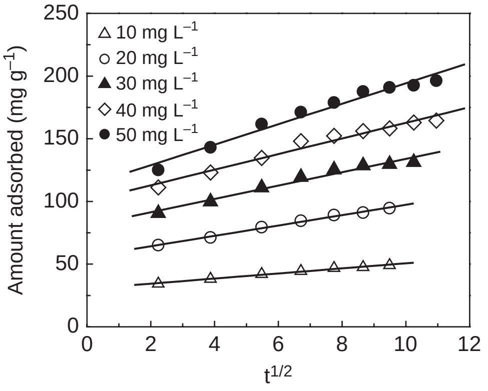

Fig. 6. Intra particle diffusion plots for different initial concentrations (adsorbent dose = 0.2 g L^{-1}; contact time = 120 min; pH = 5; temperature = 303 K).

through the origin indicating that the mechanism of Pb(II) removal on SDC was by some degree of boundary layer control further implying that the intra particle diffusion was not the only rate limiting step but also other kinetic models may control the rate of adsorption, all of which may be operating simultaneously [41,42]. The intra particle rate constant values calculated from the slopes of the linear portions of the plots of q versus t $^{1/2}$ are given in Table 3.

3.5. Effect of temperature on adsorption rate

It was observed that Pb(II) biosorption followed pseudo-second-order kinetics at different temperatures. Linear plots of t/q_t versus t corresponding to the pseudo-second-order kinetic model were obtained (Fig. 7). The values of kinetic parameters obtained are presented in Table 4. The rise in temperature increased the values of q_e and k_2. In the present investigation it was observed that the adsorption of Pb(II) increase with increase in temperature. The adsorption capacity of the metal is found to increase from196 mg g^{-1} to 235 mg g^{-1} and the rate of the reaction was almost doubled for every 10°C rise in temperature. The enhancement of adsorption capacity at higher temperature may be attributed to either increase in the number of active sites available for adsorption on the adsorbent or due to decrease in the boundary layer thickness surrounding the sorbent, so that the mass transfer resistance of adsorbate in the boundary layer decreased [43].

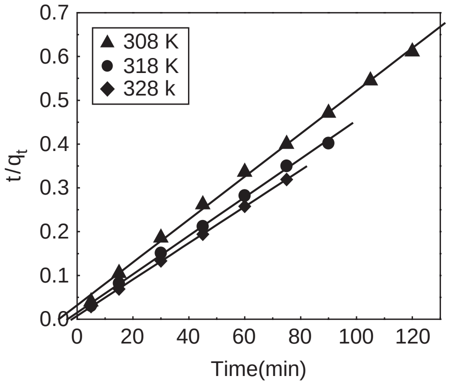

Fig. 7. Pseudo-second order kinetic plots for different temperatures (adsorbent dose = 0.2 g L^{-1}; Pb(II) concentration = 50 mg L^{-1}; pH = 5).

3.6. Adsorption dynamics

The thermodynamic equilibrium constant K_c for the adsorption was determined by using the equation $K_c = C_A/C_e$, where C_A is the amount of Pb(II) adsorbed on the adsorbent of the solution at equilibrium (mol L^{-1}) and C_e is the equilibrium concentration of Pb(II) in the solution(mol L^{-1}). The change in standard free energy, enthalpy and entropy of adsorption were calculated using the following equation:

$$\Delta G° = -RT \ln K_c, \tag{14}$$

where R is the gas constant and T the temperature (K).

According to Vant Hoff's equation:

$$\ln K_c = \Delta S°/R - \Delta H°/RT \tag{15}$$

where $\Delta S°$ and $\Delta H°$, the changes in entropy and enthalpy of adsorption respectively.

A plot of ln K_c versus $1/T$ is linear (Fig. 8). Values of $\Delta H°$ and $\Delta S°$ were evaluated from the slope and intercept of Vant Hoff's plot (Table 5). The positive value of $\Delta H°$ confirms the endothermic nature of adsorption [44]. When the temperature was increased from 30°C to 50°C, the magnitude of free energy change shifted to a high negative value suggesting that the adsorption was rapid and spontaneous [45]. The positive value of $\Delta S°$ suggested an increase in randomness at the solid–solution interface during the adsorption of Pb(II) on SDC [46].

Table 4
Comparison of the pseudo-first-order and pseudo-second-order adsorption rate constants for different temperatures.

Temperature K	Exp q_e (mg g^{-1})	Pseudo-first order			Pseudo-second order		
		$K_1 \times 10^{-2}$ (min^{-1})	Cal q_e (mg g^{-1})	R^2	$K_2 \times 10^{-3}$ g mg^{-1} min^{-1}	Cal q_e mg g^{-1}	R^2
303	196.25	3.017	87.30	0.9959	0.748	204.08	0.9990
313	223.77	2.764	59.16	0.9582	1.291	227.27	0.9993
323	234.99	5.804	57.28	0.9675	2.248	240.39	1.000

(Initial metal ion concentration–50 mg L^{-1}; pH–5; contact time–120 min; adsorbent dose 0.2 g L^{-1}).

Table 5
Thermodynamic parameters and Tempkin constant for the adsorption of Pb(II) onto SDC.

Temperature K	$-\Delta G$ kJ mol^{-1}	ΔH kJ mol^{-1}	ΔS J mol^{-1}	Tempkin isotherm constant	
				B	K_T (L g^{-1})
303	3.262			−82.253	121.049
313	5.579	60.484	210.702	−51.096	464.331
323	7.384			−38.291	1575.792

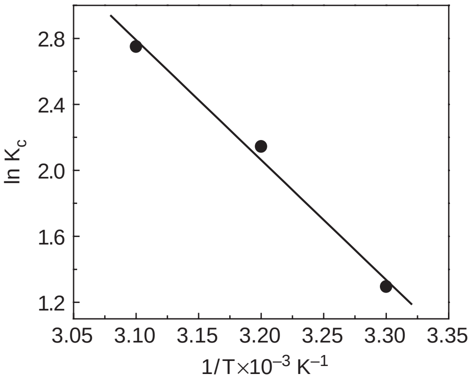

Fig. 8. Vant Hoff plot for the calculation of thermodynamic parameters for adsorption of Pb(II) onto SDC.

4. Conclusion

The present study clearly established that the sawdust of *Bombax ceiba* is an effective adsorbent for Pb(II) removal from aqueous solutions. The adsorption of Pb(II) ions was heavily dependent on the amount of adsorbent, agitation time and initial pH of the solution. Both Freundlich and Langmuir isotherms modeled the adsorption equilibrium. The mean free energy of adsorption E was determined in the D-R equation. The adsorption capacity of the sawdust is high 209 mg g^{-1} compared to other reported in the literature. The kinetics of sorption followed pseudo-second-order mechanism and also intra particle diffusion model, where diffusion is not the only rate-controlling step. The thermo dynamic calculations indicated the feasibility, endothermic and spontaneous nature of the adsorption of Pb(II) onto SDC from 303 K to 323 K. Kinetic and thermodynamic data obtained in the present study are useful for the fabrication and designing of wastewater treatment. It can be concluded that the high adsorption capacity and the endothermic nature of *Bombax ceiba* sawdust appears to be a promising adsorbent for the removal of Pb(II) ions from aqueous solution and it is an inexpensive material for treating the industrial wastewater. At these adsorption levels a process using sawdust for the removal and recovery of a heavy metal is more economical than current process technology.

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