# Chromium(VI) adsorption from aqueous solution by *Hevea Brasilinesis* sawdust activated carbon

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## Abstract

Adsorption capacity of Cr(VI) onto *Hevea Brasilinesis* (Rubber wood) sawdust activated carbon was investigated in a batch system by considering the effects of various parameters like contact time, initial concentration, pH and temperature. Cr(VI) removal is pH dependent and found to be maximum at pH 2.0. Increases in adsorption capacity with increase in temperature indicate that the adsorption reaction is endothermic. Based on this study, the thermodynamic parameters like standard Gibb's free energy ($\Delta G^\circ$), standard enthalpy ($\Delta H^\circ$) and standard entropy ($\Delta S^\circ$) were evaluated. Adsorption kinetics of Cr(VI) ions onto rubber wood sawdust activated carbon were analyzed by pseudo first-order and pseudo second-order models. Pseudo second-order model was found to explain the kinetics of Cr(VI) adsorption most effectively. Intraparticle diffusion studies at different temperatures show that the mechanism of adsorption is mainly dependent on diffusion. The rate of intraparticle diffusion, film diffusion coefficient and pore diffusion coefficient at various temperatures were evaluated. The Langmuir, Freundlich and Temkin isotherm were used to describe the adsorption equilibrium studies of rubber wood sawdust activated carbon at different temperatures. Langmuir isotherm shows better fit than Freundlich and Temkin isotherm in the temperature range studied. The result shows that the rubber wood sawdust activated carbon can be efficiently used for the treatment of wastewaters containing chromium as a low cost alternative compared to commercial activated carbon and other adsorbents reported.
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## 1. Introduction

The removal of toxic metal ions from wastewater is an important and widely studied research area. One of the heavy metals that have been a major focus in wastewater treatment is chromium. The toxicity caused by hexavalent chromium is high and therefore priority is given to regulate this pollutant at the discharge level. Industrial effluents from tanning, electroplating, paint, textile industries, etc. contains chromium species above the maximum contaminant level [1]. Even though both trivalent and hexavalent forms of chromium exists in industrial wastewater, the hexavalent form has been considered to be more hazardous due to its carcinogenic prop-

erties [2]. The permissible limit for hexavalent chromium in industrial wastewaters is 0.1 mg/l. In order to reduce Cr(VI) in these effluents to the standard level, an efficient and low cost method needs to be developed. The various methods of removal of Cr(VI) from industrial wastewater include filtration, chemical precipitation, adsorption, electrodeposition and membrane systems or even ion exchange process. Chemical precipitation and reduction process needs another separation techniques for the treatment and disposal of high quantities of waste metal residual sludge produced. These techniques use a lot of treatment chemicals and the residual Cr(VI) concentration required in the treated wastewater is not achieved because of the structure of the precipitates. The application of membrane systems for the wastewater treatment has major problems like membrane scaling, fouling and blocking. The drawback of the ion exchange process is

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**Nomenclature**

| | |
|---|---|
| $a$ | radius of the adsorbent (mm) |
| $A$ | Temkin adsorption intensity (l/g) |
| $b$ | Langmuir adsorption intensity constant (l/mg) |
| $b_f$ | Freundlich isotherm exponent |
| $B$ | Temkin constant |
| $C_0$ | initial concentration of Cr(VI) solution (mg/l) |
| $C_{Ae}$ | amount adsorbed on solid at equilibrium (mg/l) |
| $C_e$ | equilibrium concentration (mg/l) |
| $D_1$ | diffusion coefficient at the initial stage (cm$^2$/s) |
| $D_2$ | diffusion coefficient at the final stage (cm$^2$/s) |
| $\Delta G°$ | standard Gibbs energy of adsorption (kJ/mol) |
| $\Delta H°$ | standard enthalpy of adsorption (kJ/mol) |
| $k_1$ | first-order rate constant(1/min) |
| $k_2$ | second-order rate constant(g/mg min) |
| $k_{id}$ | intraparticle diffusion rate (mg/g min$^{0.5}$) |
| $k_f$ | Freundlich multilayer adsorption capacity (mg/g) |
| $K_c$ | equilibrium constant |
| $M$ | weight of the adsorbent (g) |
| $q_e$ | amount adsorbed at equilibrium (mg/g) |
| $q_t$ | amount adsorbed at time $t$ (mg/g) |
| $Q^0$ | Langmuir monolayer adsorption capacity (mg/g) |
| $\Delta S°$ | standard entropy of adsorption (J/mol k) |
| $T$ | temperature (K) |
| $V$ | volume of the solution (l) |

the high cost of the resin while the electrodeposition method is more energy intensive than other methods. Among these methods adsorption is one of the most economically favorable and a technically easy method [3].

In recent years, investigations have been carried out for the effective removal of large quantities of Cr(VI) from waste water using low cost, non-conventional adsorbents which are economically viable [4]. The main focus is on the use of various industrial wastes, agricultural byproducts and biological materials as sorbents [5]. Adsorption on activated carbon has been a popular choice in developed countries for the removal of chromium(VI) and other metallic ions [6,7]. The use of activated carbons to remove Cr(VI) from water was proposed because of their higher surface areas and active functional groups [8] leading to a search for low-cost adsorbents in recent years. Natural materials that are available in large quantities or certain waste from agricultural operations could be potential low cost adsorbents, as they represent unused resources [9]. Agricultural waste such as rice husk, maple sawdust and coconut shell [10–12] have also been used for the preparation of activated carbons and used for the removal of Cr(VI) from waste water. Agricultural byproducts like sawdust are generally used as a fuel however, the bulkiness of sawdust and its tendency towards incomplete combustion

are its drawbacks as an effective fuel. Adsorption on to low cost adsorbents, such as rubber wood sawdust activated carbon now offers an attractive and inexpensive option for the removal of chromium. The abundance and availability of rubber wood sawdust makes it economically feasible.

This paper deals with the investigation of Cr(VI) removal from aqueous solution by adsorption onto activated carbon produced from rubber wood sawdust activated carbon (RAC). The adsorption isotherms, kinetics and its mechanism at different temperatures are discussed.

## 2. Experimental procedure

### 2.1. Materials

Rubber wood sawdust used in this study was collected from Kerala, India. All the reagents used were of analytical grade. The impregnating agent for the chemical activation of the sawdust was phosphoric acid. The aqueous solution of Cr(VI) was prepared by dissolving potassium dichromate in double distilled water. The pH of the solution was varied using either sulfuric acid or sodium hydroxide.

### 2.2. Adsorbent preparation

The rubber wood sawdust, an economically low value product was considered as a possible raw material for the preparation of activated carbon. Rubber wood sawdust was washed with deionized water and dried. The dried sawdust was mixed with phosphoric acid in the ratio of 1:2 by weight and soaked for 24 h to allow the impregnating reagent to be fully adsorbed onto the raw material. The mixture was dried at 383 K for 1.5 h and then transferred to a sealed ceramic container for activation. Activation of the pretreated sawdust was carried out in a muffle furnace, the temperature and time of carbonization being 673 K and 1 h. The carbons thus produced were then repetitively washed with distilled water to recover the acid and further washed with a 1% NaHCO$_3$ solution to remove the traces of residual acid. The adsorbent was powdered and sieved. An average particle size of 0.074 mm was used for the adsorption studies. The proximate analysis of the raw material and the properties of activated carbon prepared are given in Table 1.

Table 1
Characteristics of the adsorbent

| Characteristics | Values |
|---|---|
| Ash (%) | 4.96 |
| Carbon (%) | 24.15 |
| Moisture (%) | 7.95 |
| Volatile (%) | 62.91 |
| BET surface area (m$^2$/g) | 1673.86 |
| Iodine number (mg/g) | 794.53 |
| Methylene blue number (mg/g) | 255.00 |
| Bulk density (g/ml) | 0.38 |

### 2.3. Batch adsorption studies

Batch studies were conducted in a temperature-controlled shaker using 100 ml of adsorbate solution and a fixed adsorbent dosage of 0.1 g. The agitation speed of the shaker was fixed at 200 rpm for all batch experiments. Samples at different time intervals (0–300 min) were taken and centrifuged. The concentration of the samples was analyzed in a spectrophotometer (Hitachi UV-2000 model) using 1,5-diphenylcarbazide as the complexing agent at the wavelength of 540 nm [13].

Isotherm studies were conducted in a series of 250 ml Erlenmeyer flasks. Each flasks was filled with 100 ml of Cr(VI) solution having different initial concentrations and the solution was adjusted to pH 2.0. After equilibration, the samples were separated and analyzed for their Cr(VI) content. Adsorption studies were carried out at different temperatures (303, 313 and 323 K) to obtain the equilibrium isotherms. The initial concentration of solutions taken for this study was 50, 75, 100, 150 and 200 mg/l. The equilibrium adsorption capacity was calculated using the equation below

$$q_e = \frac{(C_0 - C_e)V}{M} \tag{1}$$

where $q_e$ (mg/g) is the equilibrium adsorption capacity, $C_o$ and $C_e$ are the initial and equilibrium concentration (mg/l) of Cr(VI) ions in solution, $V$ (l) is the volume and $M$ (g) is the weight of the adsorbent.

## 3. Results and discussion

### 3.1. Effect of initial concentration and time

The amount of chromium adsorbed for different initial concentrations onto RAC is shown in Fig. 1. The adsorption of Cr(VI) onto RAC increases with time and then attains an
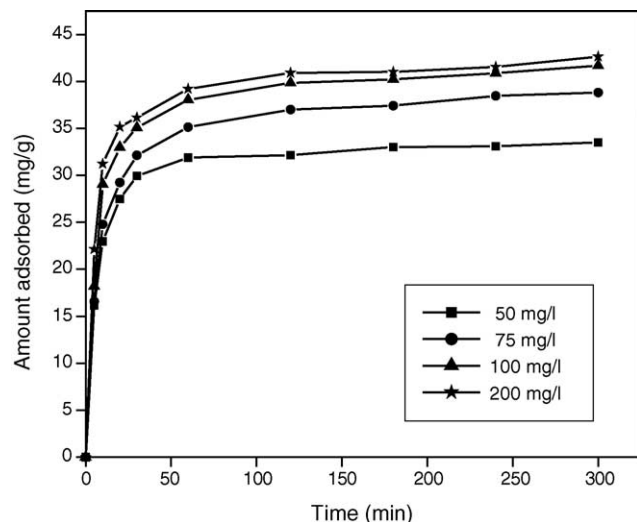
equilibrium value at a time of about 300 min. The removal of Cr(VI) was found to be dependent on the initial concentration, the amount adsorbed increasing with increase in initial concentration. Further, the adsorption is rapid in the early stages and then attains an asymptotic value for larger adsorption time. The same effect was observed on varying the temperature. At low concentrations the ratio of available surface to the initial Cr(VI) concentration is larger, so the removal becomes independent of initial concentrations. However, in the case of higher concentrations this ratio is low, the percentage removal then depends upon the initial concentration. On changing the initial concentration from 50 to 200 mg/l, the amount adsorbed increased from 33.51 to 42.64 mg/g for a time period of 300 min. The plots are smooth and continuous suggesting the possible monolayer adsorption of chromium on the surface of RAC.

### 3.2. Effect of pH

The pH of the system determines the adsorption capacity due to its influence on the surface properties of the RAC and different ionic forms of the chromium solutions. Change of the adsorption capacity of Cr(VI) on RAC with pH is shown in Fig. 2. At pH 1.0, the chromium ions exist in the form of $H_2CrO_4$, while in the pH range of 1.0–6.0 different form of chromium ions such as $Cr_2O_7^-$, $HCrO_4^-$, $Cr_3O_{10}^{2-}$, $Cr_4O_{13}^{2-}$ coexist of which $HCrO_4^-$ predominates. As pH increases this form shifts to $CrO_4^{2-}$ and $Cr_2O_7^{2-}$. Chromium exists in different oxidation states and the stability of these forms depends upon the pH of the system [14,15]. The equilibrium that exists between different ionic species of chromium are as follows:
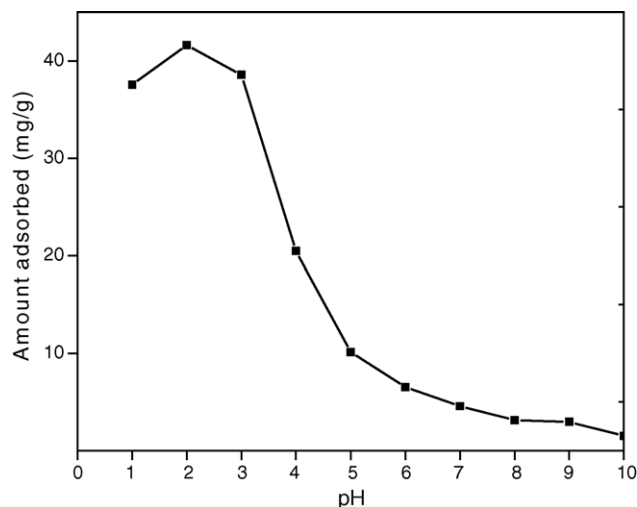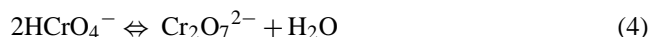
$$H_2CrO_4 \Leftrightarrow H^+ + HCrO_4^- \tag{2}$$

$$HCrO_4^{2-} \Leftrightarrow H^+ + CrO_4^{2-} \tag{3}$$

$$2HCrO_4^- \Leftrightarrow Cr_2O_7^{2-} + H_2O \tag{4}$$



Fig. 1. Effect of initial concentration and time at $T = 303$ K, pH 2.0.



Fig. 2. Effect of pH for the concentration of 200 mg/l at $T = 303$K.

From Fig. 2 it was observed that the maximum adsorption occurred at pH 2.0. Maximum adsorption at acidic pH indicates that the low pH leads to an increase in H$^+$ ions on the carbon surface this results in significantly strong electrostatic attraction between positively charged RAC surface and chromate ions. In the acidic range, where the Cr(VI) is predominately in the form of HCrO$_4^-$ the removal was found to exponentially decrease with increase in the pH since HCrO$_4^-$ ions has a greater affinity towards the hydrogen ions present on the surface of the activated carbon. However, at pH less than 2.0 a decrease is observed due to the chromium being present predominantly as H$_2$CrO$_4$. Adsorption of Cr(VI) on the activated carbon was not significant at pH values greater than 6.0 due to dual competition of both the anions (CrO$_4^{2-}$ and OH$^-$) to be adsorbed on the surface of the adsorbent of which OH$^-$ predominates. Maximum adsorption occurs at pH 2.0 and hence it was taken as the optimal value for further adsorption studies.

## 3.3. Effect of temperature

The adsorption of Cr(VI) onto RAC at different temperatures shows an increase in the adsorption capacity when the temperature is increased. The adsorption capacity varies with temperature and initial concentration as shown in Fig. 3. With increase in temperature from 293 to 323 K, the adsorption capacity increased from 20.78 to 63.99 mg/g for the initial concentration of 200 mg/l at pH 2.0. Similar trends are observed for all the other concentrations. This indicates that the adsorption reaction is endothermic in nature. The enhancement in the adsorption capacity may be due to the chemical interaction between adsorbates and adsorbent, creation of some new adsorption sites or the increased rate of intraparticle diffusion of Cr(VI) ions into the pores of the adsorbent at higher temperatures [16]. The standard Gibb's energy was
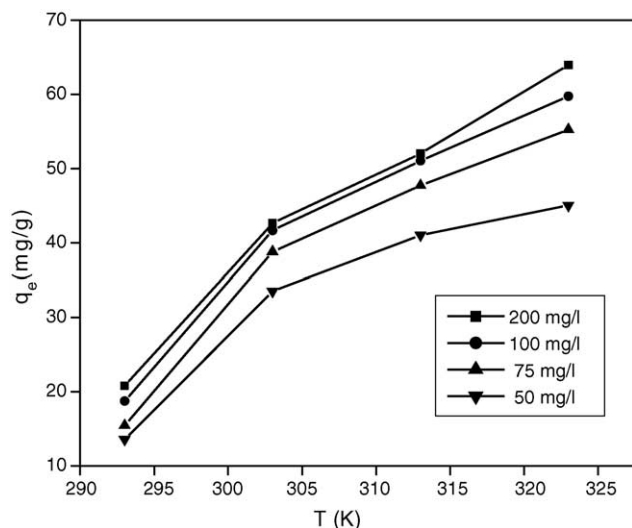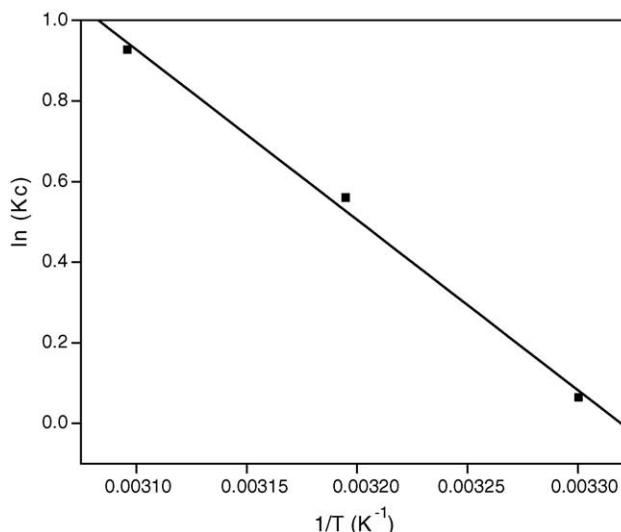


Fig. 4. Vant Hoff's plot at concentration of 75 mg/l, pH 2.0.

evaluated by

$$\Delta G^\circ = -RT \ln K_c \tag{5}$$

The equilibrium constants $K_c$ was evaluated at each temperature using the following relationship

$$K_c = \frac{C_{Ae}}{C_e} \tag{6}$$

where $C_{Ae}$ is the amount adsorbed on solid at equilibrium and $C_e$ is the equilibrium concentration.

The other thermodynamic parameters such as change in standard enthalpy ($\Delta H^\circ$) and standard entropy ($\Delta S^\circ$) were determined using the following equations

$$\ln K_c = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \tag{7}$$

$\Delta H^\circ$ and $\Delta S^\circ$ were obtained from the slope and intercept of the Van't Hoff's plot of $\ln K_c$ versus $1/T$ as shown in Fig. 4. Positive value of $\Delta H^\circ$ indicates that the adsorption process is endothermic. The negative values of $\Delta G^\circ$ reflect the feasibility of the process and the values become more negative with increase in temperature. Standard entropy determines the disorderliness of the adsorption at solid–liquid interface. Table 2 summarizes the results.

## 3.4. Adsorption kinetics

The kinetics of adsorption describes the rate of uptake of chromium ions onto the activated carbon and this rate con-



Fig. 3. Effect of temperature for the concentration of 200 mg/l at pH 2.0.

Table 2
Thermodynamic parameters of RAC at initial concentration of 75 mg/l, pH 2.0

| T (K) | $\Delta G^\circ$ (kJ/mol) | $\Delta H^\circ$ (kJ/mol) | $\Delta S^\circ$ (J/mol k) |
|---|---|---|---|
| 303 | −0.162 | | |
| 313 | −1.458 | 35.144 | 116.58 |
| 323 | −2.490 | | |

Table 3
Adsorption kinetic model rate constant of RAC at different temperatures

| $T$ (K) | $C_0$ (mg/l) | $q_e$ (exp) (mg/g) | Pseudo first-order | | | Pseudo second-order | | |
|---|---|---|---|---|---|---|---|---|
| | | | $K_1 \times 10^{-3}$ (1/min) | $q_e$ (cal) (mg/g) | $R^2$ | $K_2 \times 10^{-3}$ (g/mg min) | $q_e$ (cal) (mg/g) | $R^2$ |
| 303 | 50 | 33.51 | 14.46 | 8.50 | 0.8630 | 3.876 | 33.49 | 0.9995 |
| | 100 | 41.68 | 12.53 | 12.34 | 0.8900 | 3.671 | 42.19 | 0.9999 |
| | 200 | 42.64 | 10.52 | 9.85 | 0.8070 | 4.698 | 42.57 | 0.9996 |
| 313 | 50 | 41.08 | 17.54 | 10.37 | 0.9121 | 3.967 | 40.09 | 0.9958 |
| | 100 | 51.16 | 15.23 | 12.54 | 0.8903 | 4.482 | 51.01 | 0.9998 |
| | 200 | 57.04 | 12.26 | 11.18 | 0.8411 | 5.225 | 56.99 | 0.9995 |
| 323 | 50 | 43.37 | 19.45 | 8.00 | 0.8581 | 4.125 | 43.63 | 0.9998 |
| | 100 | 63.21 | 21.79 | 12.52 | 0.9234 | 5.332 | 63.81 | 0.9999 |
| | 200 | 63.99 | 16.58 | 10.50 | 0.8407 | 5.718 | 64.44 | 0.9997 |

trols the equilibrium time. This study reveals that 60–70% of the adsorption takes place within the first hour of contact. The amount of metal ions removed in the first hour of contact increases as the concentration of the metal ion increases. The effect of temperature on the uptake rate of metal ions shows that the rate of removal increased with an increase in temperature. The kinetics of Cr(VI) onto RAC were analyzed by pseudo first-order and pseudo second-order mechanisms at different temperatures. The experimental data and model predicted data were compared based on the regression coefficient ($R^2$) are shown in Table 3.

Adsorption kinetic data were treated with pseudo first order rate Eq. [17]

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303}t \tag{8}$$

where $q_e$ (mg/g) denotes equilibrium concentration of Cr(VI) in solution, $q_t$ (mg/g) represents residual concentration and $k_1$ (1/min) is the first-order rate constant. The $R^2$ values shows that the adsorption of Cr(VI) onto RAC does not follow first-order kinetics.

The pseudo second-order model can be represented as [18]

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e}t \tag{9}$$

where $k_2$ (g/mg min) is the second order rate constant. The calculated $q_e$ values agree very well with experimental values and regression coefficient of above 0.99 confirms that the adsorption phenomena followed second order kinetics. Similar results have been observed in the adsorption of Cr(VI) by used tyres and sawdust [15].

### 3.5. Adsorption mechanism

Intraparticle diffusion model is of major concern because it is rate-determining step in the liquid adsorption systems. The intraparticle diffusion varies with square root of time is given by [19] as
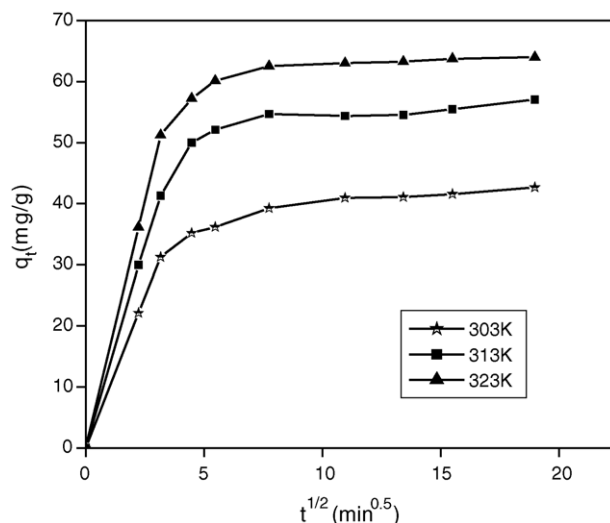
$$q_t = k_{id}t^{1/2} \tag{10}$$



Fig. 5. Intraparticle diffusion plot at different temperatures for the initial concentration 200 mg/l, pH 2.0.

$q_t$ is the amount adsorbed at a time (mg/g), $t$ is the time (min), $k_{id}$ (mg/g min$^{0.5}$) is the rate constant of intraparticle diffusion. The intraparticle diffusion rate constant was determined from the slope of the linear gradients of the plot $q_t$ versus $t^{1/2}$ as shown in Fig. 5. The rate constant of intraparticle diffusion at different temperatures is shown in Table 4. The intraparticle diffusion process is controlled by the diffusion of ions within the adsorbent. The initial curved portion relates to the film diffusion ($D_1$) and the latter linear portion represents the diffusion ($D_2$) within the adsorbent. Assuming adsorbent particle to be sphere of radius '$a$' and the diffusion follows Fick's law, the relationship between weight uptake and time

Table 4
Intraparticle rate parameter and diffusion coefficients at different temperatures

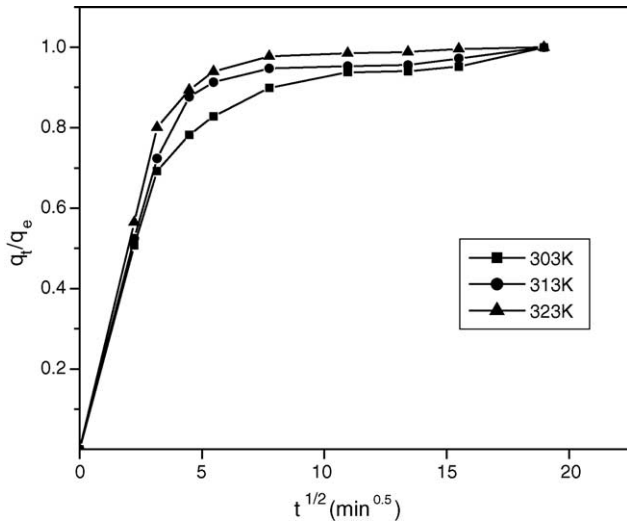| $T$ (K) | $k_{id}$ (mg/g min$^{0.5}$) | $D_1 \times 10^{-10}$ (cm$^2$/s) | $D_2 \times 10^{-10}$ (cm$^2$/s) |
|---|---|---|---|
| 303 | 8.50 | 7.563 | 1.228 |
| 313 | 12.03 | 8.856 | 1.457 |
| 323 | 14.25 | 9.866 | 1.828 |

Fig. 6. Determination of diffusion coefficient ($D_1$) for the initial concentration 200 mg/l, pH 2.0 at different temperatures.

is given by [20]

$$\frac{q_t}{q_e} = 6\left(\frac{Dt}{a^2}\right)^{1/2}\left\{\pi^{-1/2} + 2\sum_{n=1}^{\infty}\mathrm{ierfc}\frac{na}{\sqrt{(Dt)}}\right\} - 3\frac{Dt}{a^2} \tag{11}$$

At small times, the $D$ is replaced by $D_1$ and Eq. (11) reduces to

$$\frac{q_t}{q_e} = 6\left(\frac{D_1}{\pi a^2}\right)^{1/2} t^{1/2} \tag{12}$$

$D_1$ is calculated from the slope of the plot of $q_t/q_e$ versus $t^{1/2}$ as shown in Fig. 6. For moderate and large times, the relation between weight uptake and diffusion equation is

$$\frac{q_t}{q_e} = 1 - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-Dn^2\pi^2 t}{a^2}\right) \tag{13}$$

As $t$ tends to large times, the Eq. (13) can be written in the form

$$\ln\left(1 - \frac{q_t}{q_e}\right) = \ln\frac{6}{\pi^2} - \left(\frac{D_2\pi^2}{a^2}t\right) \tag{14}$$

where $D$ is replaced by $D_2$.

$D_2$ is calculated from the slope of the plot of $\ln(1 - q_t/q_e)$ versus $t$ as shown in Fig. 7.

The values of $D_1$ the film diffusion and $D_2$ the pore diffusion coefficient are shown in Table 4 at different temperatures. Increase in temperature shows an increase in both $D_1$ and $D_2$ for an initial concentration of 200 mg/l at pH 2.0. The large negative exponential values of the same order of magnitude indicate that both film diffusion as well as pore diffusion controls the adsorption mechanism. Further since both $D_1$ and $D_2$ increase with temperature, the adsorption capacity increase with temperature is validated. At pH 2.0 the dominant form of Cr(VI) ions is $HCrO_4^-$ the $D_1$ and $D_2$ values reflect the diffusion of $HCrO_4^-$ into the adsorbent.
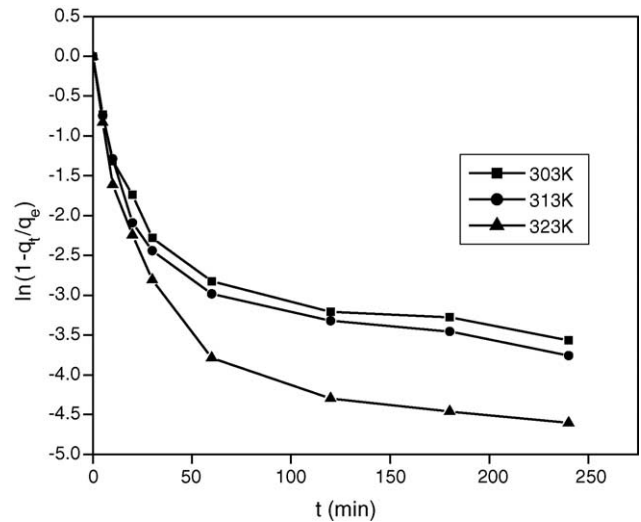


Fig. 7. Determination of diffusion coefficient ($D_2$) for the initial concentration 200 mg/l, pH 2.0 at different temperatures.

### 3.6. Adsorption isotherms

Adsorption equilibrium data were fitted to the Langmuir, Freundlich and Temkin isotherms at various temperatures. Langmuir isotherm is based on the monolayer adsorption of chromium ions on the surface of carbon sites and is expressed in the linear form as [15]

$$\frac{C_e}{q_e} = \frac{1}{Q^0 b} + \frac{C_e}{Q^0} \tag{15}$$

where $C_e$ is the equilibrium concentration (mg/l) and $q_e$ the amount adsorbed at equilibrium (mg/g). The Langmuir constants $Q^0$ (mg/g) represent the monolayer adsorption capacity and $b$ (l/mg) relates the heat of adsorption.

Freundlich isotherm describes the heterogeneous surface energies by multilayer adsorption and is expressed in linear form as [21]

$$\ln q_e = \ln K_f + b_f \ln C_e \tag{16}$$

where $K_f$ indicates adsorption capacity (mg/g) and $b_f$ an empirical parameter related to the intensity of adsorption, which varies with the heterogeneity of the adsorbent. For values in the range $0.1 < b_f < 1$, adsorption is favorable [22]. The greater the values of $b_f$ better is the favorability of adsorption.

Temkin isotherm based on the heat of adsorption of the ions, which is due to the adsorbate and adsorbent interactions taken in linear form, is given by [21]

$$q_e = \left(\frac{RT}{b}\right)\ln A + \left(\frac{RT}{b}\right)\ln C_e \tag{17}$$

$$\frac{RT}{b} = B \tag{18}$$

where $A$ (l/g) and $B$ are Temkin constants.

Table 5
Adsorption isotherms of RAC at different temperatures

| $T$ (K) | Langmuir constants | | | Freundlich constants | | | Temkin constants | | |
|---|---|---|---|---|---|---|---|---|---|
| | $Q^0$ (mg/g) | $b$ (l/mg) | $R^2$ | $K_f$ (mg/g) | $b_f$ | $R^2$ | $B$ | $A$ (l/g) | $R^2$ |
| 303 | 44.05 | 0.2215 | 0.9998 | 25.48 | 0.1070 | 0.9230 | 4.332 | 173.05 | 0.9735 |
| 313 | 59.17 | 0.2387 | 0.9993 | 31.71 | 0.1215 | 0.9938 | 5.897 | 118.66 | 0.9978 |
| 323 | 65.78 | 0.2443 | 0.9988 | 34.81 | 0.1344 | 0.9345 | 6.894 | 100.92 | 0.9492 |

The theoretical parameters of isotherms along with regression coefficient are listed in Table 5. The isotherms are compared based on the parameter values with experimental data at 303 K as shown in Fig. 8. From Table 5, it was observed that the Langmuir monolayer adsorption capacity increased by 49.33%, whereas the Freundlich multilayer adsorption capacity was found to increase by 36.62% with an increase in temperature from 303 to 323 K. Temkin isotherm constants at different temperatures from Table 5 show that there is the linear fall in the standard enthalpy of adsorption with surface coverage. The Langmuir isotherm model has higher regression coefficient when compared to the other models shows the homogeneous nature of the adsorbent. Increases in Langmuir constant $b$ with temperature confirms the endothermic nature of adsorption and Freundlich constant $b_f$ shows the favorability of adsorption at higher temperatures.

## 3.7. Comparison of RAC with other adsorbents

The adsorption capacity of Cr(VI) onto RAC was compared with other adsorbents reported in literature and is shown in Table 6. It can be observed that a pH of 2.0 was found to be an optimum in nearly all cases whatever be the method of activation. This is in keeping with the fact that the Cr(VI) get reduced to Cr(III) to a large extent at pH close to 1.0. Further, it can also be seen that the activated carbon

Table 6
Comparison of adsorption capacities of Cr(VI) with other adsorbents

| Adsorbents | Adsorption capacity (mg/g) | pH | Co (mg/l) | Reference |
|---|---|---|---|---|
| Leather | 459.00 | 2.0 | 1000 | [23] |
| HSAC | 170.00 | 1.0 | 1000 | [24] |
| Tyres activated carbon | 58.50 | 2.0 | 60 | [15] |
| F400 | 48.54 | 2.0 | 60 | [15] |
| Leaf mould | 43.10 | 2.0 | 1000 | [14] |
| Coconut shell carbon | 20.00 | 2.0 | – | [25] |
| HSAC | 17.70 | 2.0 | 30 | [26] |
| Beech sawdust | 16.10 | 1.0 | 200 | [27] |
| Sugarcane bagasse | 13.40 | 2.0 | 500 | [28] |
| Coconut shell carbon | 10.88 | 4.0 | 25 | [12] |
| Treated sawdust of Indian Rosewood | 10.00 | 3.0 | 100 | [29] |
| Coconut tree sawdust | 3.60 | 3.0 | 20 | [4] |
| RAC | 44.05 | 2.0 | 200 | Present study |

produced from rubber wood sawdust compares well with the activated carbons from most of the raw materials listed in Table 6. Leather, tyres are a few raw materials that exhibited very high adsorption capacity, this could be primarily due to the initial carbon content, activation process as well as the pore development due to the basic morphology of the raw material. Hence, RAC can be considered to be viable adsorbent for the removal of Cr(VI) from dilute solutions.

## 4. Conclusion

*Hevea Brasilinesis* sawdust, a waste product was converted into a carbonaceous adsorbent and used for the removal of Cr(VI) from wastewater. The activated carbon from rubber wood was proved to be a good adsorbing medium for Cr(VI). Adsorption of Cr(VI) is found to be effective in the lower pH range and at higher temperatures. Increase in adsorption capacity with rise in temperature reveals that the adsorption is chemical in nature and the process is endothermic, which is confirmed by the thermodynamical parameters evaluated. The Langmuir isotherm fits the data better than the Freundlich and Temkin isotherms. Thus, the results shows that the activated carbon from rubber wood sawdust can be effectively applied for the removal of Cr(VI) from wastewater. Easy availability and suitability for the production of activated carbon from rubber wood sawdust makes it one of
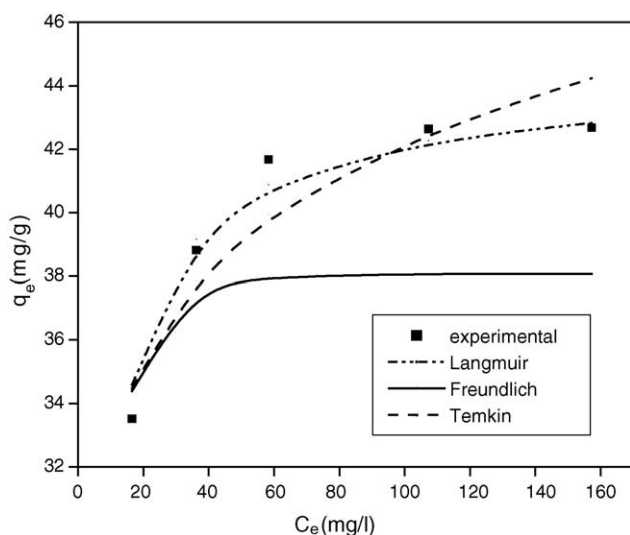


Fig. 8. Adsorption isotherms at pH 2.0 and $T = 303$ K.

the biomass waste that can be effectively utilized for removal of Cr(VI) from waste waters.

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