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O. Abdelwahab^a; A. El Sikaily^a; A. Khaled^a; A. El Nemr^a

^a Environmental Division, National Institute of Oceanography and Fisheries, Alexandria, Egypt

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Mass-transfer processes of chromium(VI) adsorption onto guava seeds

O. ABDELWAHAB, A. EL SIKAILY, A. KHALED and A. EL NEMR*

Environmental Division, National Institute of Oceanography and Fisheries,
Kayet Bay, El-Anfushy, Alexandria, Egypt

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The chromium(VI) biosorption onto guava seeds, as an alternative method for Cr^{6+} removal from aqueous solutions, was investigated. The parameters affecting kinetics and equilibrium of Cr^{6+} adsorption onto guava seeds were studied. An external mass-transfer diffusion coefficient k and intra-particle diffusion coefficient k_i were determined to measure the rate-limiting step of adsorption. A single external mass-transfer diffusion model and intra-particle diffusion models were used. The effects of initial pH, sorbent mass, and initial Cr^{6+} concentrations on mass-transfer coefficients were investigated. The external mass-transfer coefficient has an average value of $7.2 \times 10^{-3} \text{ cm s}^{-1}$, while the intra-particle mass-transfer diffusion coefficient was $0.34 \text{ mg g}^{-1} \text{ min}^{-0.5}$. This indicates that external diffusion to the guava seeds surface and intra-particle diffusion are both involved in the sorption process. The isotherm equilibrium data were well fitted by the Langmuir and Freundlich models with an average correlation coefficient $R^2 = 0.98$. The maximum removal of Cr^{6+} was obtained at pH 1 (about 100% for adsorbent dose of 15 g l^{-1} and 25 mg l^{-1} initial concentration of Cr^{6+}). The results indicated that the guava seeds exhibit acceptable sorption capacity.

Keywords: Guava seed; Chromium(VI) removal; adsorption; mass transfer; wastewater treatment; water pollution

1. Introduction

Water pollution due to toxic heavy metals has been a major cause of concern for chemists and environmentalist. Failure in treatment of the industrial and domestic wastewater is responsible for causing severe damage to the environment and adversely affecting human health. Chromium is one of the toxic heavy metals that can exist in hexavalent and trivalent forms. The main sources of chromium are mining, leather tanning, ink, dye, cement industries, electroplating, the production of alloys, photographic materials, corrosive paints, and aluminium-manufacturing industries [1–3]. The hexavalent form is more toxic than the trivalent form and is of greater concern [4]. The trivalent form of chromium is about 1000 times less toxic than Cr^{6+} . Furthermore, it has a limited solubility, making it relatively immobile

*Corresponding author. Email: ahmedmoustafaelnemr@yahoo.com

and less available for biological uptake. Hexavalent chromium form is directly toxic to bacteria, plants, and animals. Moreover, Cr^{6+} is a skin and mucous-membrane irritant, and some hexavalent compounds produce an allergic-contact dermatitis characterized by eczema; it is also recognized as a pulmonary carcinogen [5]. Because of these potential health hazards, the maximum levels permitted in waste water are 5 mg l^{-1} for Cr^{3+} and 0.05 mg l^{-1} for Cr^{6+} [1–3].

The main strategy for removal of Cr^{6+} from wastewater is reduction to Cr^{3+} and precipitation in the form of $\text{Cr}(\text{OH})_3$. The major disadvantage of this treatment method is the high cost of chemicals used for the reduction process and incomplete reduction of Cr^{6+} , which may produce toxic sludge [6]. Ion exchange [7, 8] and membrane filtration [9] are also used in Cr^{6+} removal from wastewater. However, these methods are not economically feasible for small-scale industries prevalent in developing economies due to the huge capital investment and operational costs involved.

Recently, a promising alternative method for removal of Cr^{6+} has involved sorption by solid agriculture waste. A wide range of agriculture wastes have been examined, such as sugar-beet pulp [10], wheat bran [11], saw dust [12], rice bran [13], and hydroxide-loaded sugar-beet pulp [14].

Guava seeds are an agriculture waste product produced from guava-juice processing, and the product has no economic value. The seeds represent about 5% of the fresh fruit [15] and consist of 31.4% cellulose, 14.3% hemicellulose, 40.2% lignin, 6.96% soluble compounds, 6.51% moisture, and a negligible amount of ash [16].

The aim of the present work is to study the mechanism of adsorption of Cr^{6+} onto guava seeds, and to identify the rate-controlling steps for chromium removal. Furthermore, the study proposes appropriate models for the kinetics of removal in batch reactors. The equilibrium isotherms were then analysed using Langmuir and Freundlich models, and the equilibrium sorption parameters were determined.

2. Material and methods

2.1 Preparation of adsorbent and Cr^{6+} solutions

Guava seeds were collected from a guava-juice processing plant in Alexandria, Egypt. The collected seeds were rinsed with distilled water and then dried in an oven at 105°C for 72 h. The raw seeds were ground to a particle size ranging from 0.3 to 0.8 mm ($d_p = 550 \mu\text{m}$).

Cr^{6+} solutions of varying concentrations were prepared by diluting the 1000 mg l^{-1} stock solution to the required initial concentrations. The stock solution of Cr^{6+} was obtained by dissolving the exact quantity of potassium dichromate in 1 l of double distilled water. The initial pH was adjusted to the required value for adsorption before mixing with sorbent material using 0.1 M HCl and 0.1 M NaOH. All the chemicals reagent used in this study were of reagent grade. Double-distilled water was used for preparing all of the solutions and reagents. Cr^{6+} concentration was measured using the UV-visible spectro-photometric method based on the reaction of Cr^{6+} and diphenyl carbazide (G.R., E. Merck) which forms a red-violet-coloured complex [17]. The absorbance of the coloured complex was measured in a double-beam spectrophotometer (Milton Roy, Spectronic 21D) at a wavelength, λ_{max} , of 540 nm.

2.2 Batch adsorption studies

Adsorption of Cr^{6+} on guava seeds was carried out by adding certain mass of adsorbent to 100 ml of a dichromate solution of 75 mg l^{-1} initial concentration at different pHs (1–6).

The adsorption experiments were carried out at room temperature ($25 \pm 2^\circ\text{C}$). The solutions were agitated in a rotary shaker, and the continuous mixing was provided during the experimental period using an agitation speed of 150 rpm. Samples (0.25 ml) were taken at 5-min intervals in the beginning of experiment then every 15 min until equilibrium was reached at 120 min. The solution was centrifuged using a micro-centrifuge, and the supernatant was analysed for the remaining concentration of Cr^{6+} in each sample. In order to investigate the effect of adsorbent mass, 0.5–1.5 g of guava seeds was used at the optimum pH. The effects of different initial chromium concentrations ($25 \sim 75 \text{ mg l}^{-1}$) were studied for different weights of guava seeds using the same interval of contact time as that described above. To check the repeatability of the experimental data, each experiment was conducted three times. The percentage of Cr^{6+} removal and amount adsorbed (mg g^{-1}) were calculated using the following relationships:

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

$$\text{Amount adsorbed } (q_e) = \frac{(C_i - C_f)}{m_s}, \quad (2)$$

where C_i and C_f are the initial and final concentration (mg l^{-1}) of Cr^{6+} , respectively, and m_s is the mass concentration of guava seeds (g l^{-1}).

2.3 Theory

The effective rate of adsorption is determined by one or more of several steps [18]:

- (1) mass transfer from the bulk of the liquid phase to the surfaces of the adsorbent particles;
- (2) adsorption of solute onto sorbent sites;
- (3) transfer of the chromium from the surface to the intra-particle active sites.

Generally, step 2 is usually considered very fast and was neglected in the rate-determining steps. Consequently, the rate-determining steps are the external mass transfer and intra-particle diffusion [19]. Determining of the rate-limiting steps in sorption is necessary in order to define the rate parameters for design purposes. The development of models including two such mass-transport steps is quite difficult. Therefore, simplifying assumptions were made to describe the adsorption processes in terms of an external mass-transfer coefficient in the early stages of the adsorption process and intra-particle mass-transfer diffusion coefficient.

2.3.1 External mass-transfer model. In a well-agitated batch adsorber, mixing in the liquid phase is rapid; hence, it is assumed that the concentration of adsorbent particles is uniform inside the vessel. The change in chromium concentration with time (C_t) is related to the liquid–solid mass-transfer coefficient, k , by the following equation [20, 21]:

$$\frac{dC_t}{dt} = -kS(C_t - C_s), \quad (3)$$

where S is the specific surface area for mass transfer; C_t and C_s are the liquid phase solute concentration at time t and the particle surface, respectively. At $t = 0$, $C_t = C_0$, and C_s is

negligible. Accordingly, the previous equation can be simplified to

$$\left[\frac{d(C_t/C_0)}{dt} \right]_{t \rightarrow 0} = -kS. \quad (4)$$

Assuming spherical particles of adsorbent, S can be calculated from the following relation [18]:

$$S = \frac{6m_s}{d_p \rho (1 - \varepsilon_p)}, \quad (5)$$

where d_p is the average diameter of adsorbent particles (cm), ρ is the adsorbent true density (g cm^{-3}), ε_p is the porosity of particles, and m_s is the mass concentration of the sorbent in the solution and can be determined from the relation

$$m_s = \frac{m}{V}, \quad (6)$$

where m is the mass of adsorbent in the adsorber (g), and V is the volume of solution in the adsorber (cm^3). The external mass-transfer coefficient, k , could be obtained from equation (4) after calculating the slope of plot (C_t/C_0) vs. time, but this relation was strictly valid at $t = 0$.

2.3.2 Intra-particle mass-transfer model. The rate of intra-particle diffusion is calculated from the relation of Weber and Morris [22]:

$$q = k_i t^{0.5}, \quad (7)$$

where q is the amount adsorbed per unit mass of the adsorbent (mg g^{-1}), and k_i is the intra-particle diffusion rate constant ($\text{mg g}^{-1} \text{min}^{-0.5}$). The values of k_i were calculated from the slopes of the linear plots of q vs. $t^{0.5}$.

3. Results and discussion

Table 1 reports the percentage of removal calculated from equation (1) at equilibrium pH 1.0. The percentage removal increased with increasing concentration of guava seeds but decreased with increasing chromium concentration.

Table 1. Percentage of removal of different chromium concentrations over different biomass concentrations.

Cr ⁶⁺ concentration (mg l^{-1})	Guava seeds (g l^{-1})	Removal (%)
25	5	72.83
	7.5	83.81
	10	98.75
	12.5	99.75
	15	100
50	5	69.12
	7.5	77.95
	10	85.8
	12.5	92.15
	15	98.01
75	5	66.29
	7.5	75.09
	10	86.88
	12.5	93.02
	15	96.26

3.1 Kinetic studies

All the experiments were undertaken at constant high agitation speed to achieve complete mixing of the solution and consequently complete external surface coverage of the Cr^{6+} on the particles of guava seeds. The values of external mass-transfer coefficient k and the intra-particle diffusion coefficient, k_i , were determined at different pHs, various masses of adsorbent, and different initial dye concentrations.

3.1.1 Effect of pH. The effect of pH on the external diffusion rates is given by the plot of C_t/C_0 vs. time (figure 1). The data were plotted for dye concentration 75 mg l^{-1} using 15.0 g l^{-1} of guava seeds. The external film mass-transfer coefficient, k , can be determined from the slope at $t = 0$ (equation (4)). The data indicate that the pH of the solution is an important parameter affecting the adsorption of heavy-metal ions. Figure 1 shows that the external mass-transfer coefficient decreases with any increases in pH. The maximum adsorption takes place at pH 1.0. This behaviour can be explained without considering the nature of the adsorbent. At a low pH, the adsorbent surface might have exposed more functional groups of positive charge. It is likely that a positive charge develops on the surface of an adsorbent in an acidic medium, resulting in a higher adsorption of anionic Cr^{6+} molecules, which led to an increase in the external mass-transfer coefficient [6, 23]. Furthermore, chromium, which may exist in the form of HCrO_4^- at pH 1, is adsorbed preferentially on the adsorbents, whereas increasing the pH from 1 to 6 shifts the concentration of the HCrO_4^- form to CrO_4^{2-} and $\text{Cr}_2\text{O}_7^{2-}$ forms which are less well adsorbed to the adsorbents [24].

The intra-particle diffusion coefficient k_i was determined by plotting the amount of dye adsorbed per mass of adsorbent q against the square root of time $t^{0.5}$ (equation (7)). The data are presented in figure 2. The plots were found to be linear with regression coefficients of 0.89–0.99. This linearity of the data proves that the intra-particle diffusion is an important factor in the sorption-rate determination step. The values of diffusion mass-transfer coefficient were calculated from the slopes and are shown in table 2. It is obvious that k_i increases with decreasing pH, which is an acceptable result due to the increase in external mass transfer at the corresponding values of pH.

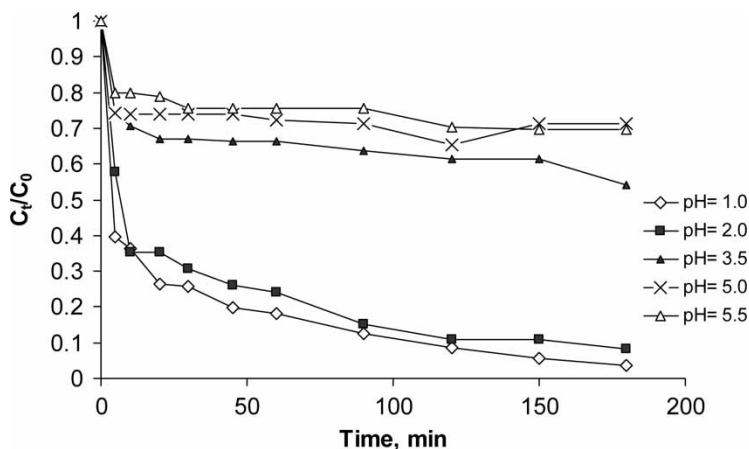


Figure 1. Effect of pH on the adsorption of Cr^{6+} at an initial concentration of 75 mg l^{-1} using 15.0 g l^{-1} of guava seeds.

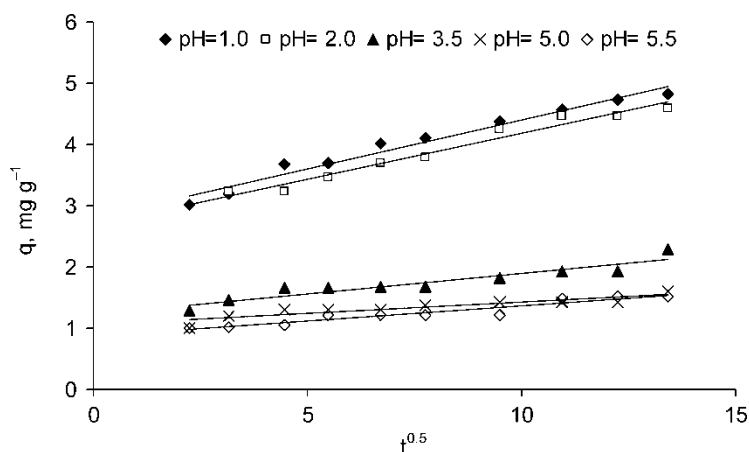


Figure 2. Intra-particle mass transfer diffusion model for different initial pHs using an initial Cr^{6+} concentration of 75 mg l^{-1} and 15.0 g l^{-1} guava seeds.

3.1.2 Effect of sorbent mass and Cr^{6+} concentrations. Figure 3 shows the effect of adsorbent concentration using 75 mg l^{-1} initial concentrations of Cr^{6+} and five different concentrations of guava seeds ($5, 7.5, 10, 12.5,$ and 15 g l^{-1}). Figure 3 represented that more than 50% of the Cr^{6+} biosorption was completed within 10 min, and equilibrium was reached after 3 h. In all cases, the rate of Cr^{6+} uptake increases with increasing mass of sorbent. Small masses of adsorbent materials have a small amount of external area exposed to the chromium molecules, and therefore the driving force of adsorption increases per unit surface area of guava seeds, whereas increasing the initial Cr^{6+} concentration led to a decrease in the initial external mass transfer for a constant mass of sorbent [19].

The intra-particle diffusion coefficients were also calculated for different masses of sorbent using 75 mg l^{-1} initial concentrations of Cr^{6+} (figure 4; table 3). The plots were found to be linear, which also proves the importance of intra-particle diffusion in the sorption-rate determination step. The value of k_i increases with increasing mass of guava seeds. This can be explained by increasing in the number of pore due to increase in the mass of sorbent.

Weber and Morris [22] have assumed that if the uptake of the adsorbate varies with the square root of time, then intra-particle diffusion step controls the process of adsorption. Simultaneously, Ho and McKay [25] have shown that it is essential for the plots of q against $t^{0.5}$

Table 2. Effect of pH on external mass transfer coefficient and intra-particle diffusion coefficient for different masses of guava seeds.

Mass (mg l^{-1})	pH	$k \times 10^3$ (cm s^{-1})	k_i ($\text{mg l}^{-1} \text{ min}^{-0.5}$)
7.5	1	7.33	0.267
	2	6.92	0.249
	3.5	3.42	0.104
	5	1.99	0.081
	5.5	1.78	0.085
15	1	6.34	0.159
	2	5.82	0.149
	3.5	1.4	0.067
	5	1.03	0.04
	5.5	1.03	0.049

Note: Standard errors for estimated parameters k and k_i were $<3.5\%$.

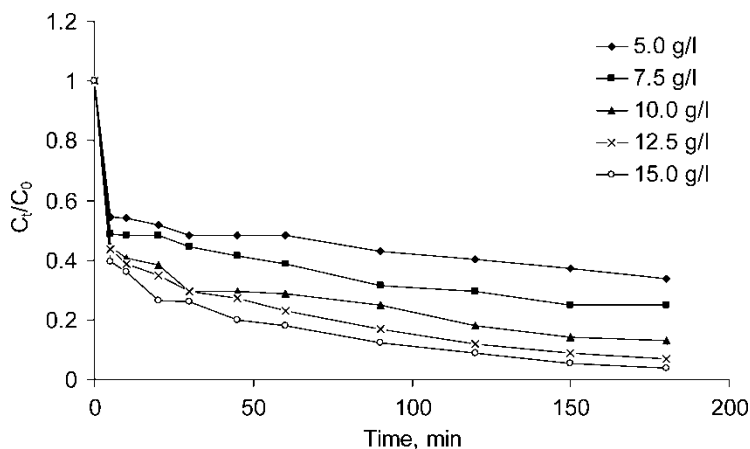


Figure 3. Effect of different sorbent concentrations on the adsorption of Cr^{6+} at optimum initial pH 1 using an initial metal concentration of 75 mg l^{-1} .

to pass through the origin if the intra-particle diffusion is the rate-limiting step of adsorption. Since this was not the case in the present work, it may be concluded that both surface adsorption and intra-particle diffusion were concurrently operating the process of adsorption of Cr^{6+} onto guava seeds. Moreover, sorption of Cr^{6+} onto guava seeds is concentration-dependent, and the increase in sorbate concentration increases the rate of pore diffusion. These also confirm the fact that adsorption of the Cr^{6+} onto guava seeds was controlled by both external surface and diffusion into the interior.

3.2 Adsorption equilibrium isotherm

The analysis of equilibrium data for adsorption of Cr^{6+} on guava seeds has been done according to Langmuir and Freundlich isotherm models. The linear form of Langmuir and Freundlich

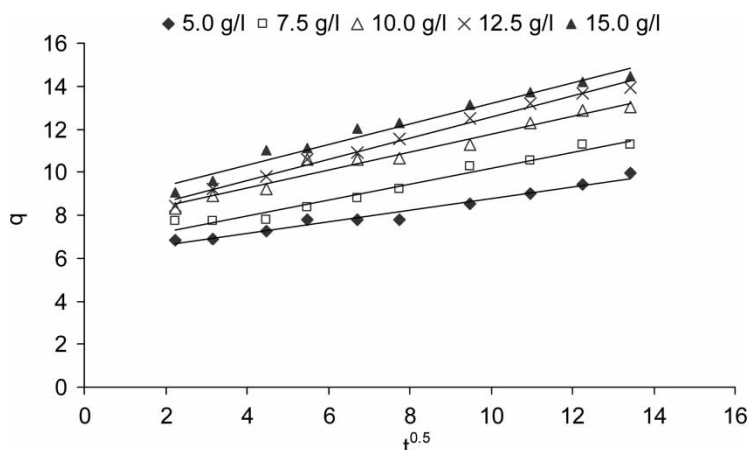


Figure 4. Intra-particle mass-transfer diffusion model at different sorbent concentrations at pH 1 and an initial Cr^{6+} concentration of 75 mg l^{-1} .

Table 3. Effect of guava-seed mass on external mass transfer coefficient and intra-particle diffusion coefficient at various Cr^{6+} concentrations.

Cr^{6+} concentration (mg l^{-1})	Adsorbent concentration (g l^{-1})	$k \times 10^{-1}$ (cm S^{-1})	k_i ($\text{mg g}^{-1} \text{min}^{-0.5}$)
50	5	3.9	0.202
	7.5	5.65	0.249
	10	8.11	0.289
	12.5	12.11	0.301
	15	17.66	0.312
75	5	3.7	0.273
	7.5	5.65	0.368
	10	8.52	0.417
	12.5	10.99	0.496
	15	14.89	0.476

Note: Standard errors for estimated parameters k and k_i were <2.5%.

isotherm models can be represented by the following equations, respectively:

$$\frac{C_e}{q_e} = \frac{1}{K_L b} + \frac{C_e}{K_L} \quad (8)$$

$$\log q_e = \log K_F + n \log C_e, \quad (9)$$

where C_e is the Cr^{6+} equilibrium concentration, K_L and b are Langmuir constants, and K_F and n are Freundlich constants which can be determined by regression of the experimental data. The experimental data yielded good linear plots with both the Langmuir isotherm (figure 5) and Freundlich isotherm (figure 6). The estimated model parameters with correlation coefficient (R^2) are shown in table 4. K_L (mg g^{-1}) which is the measure of adsorption capacity under experimental conditions was found 10.5 mg g^{-1} . The essential characteristic of the Langmuir isotherm may be expressed in terms of dimensionless equilibrium parameter R_L [26].

$$R_L = \frac{1}{1 + bC_0}. \quad (10)$$

The values of R_L for the studied system were 0.061, 0.080, and 0.108 for 25, 50, and 75 mg l^{-1} Cr^{6+} concentration, respectively. R_L values lie between 0 and 1, showing favourable adsorption of Cr^{6+} onto guava seeds. The values also indicated that the adsorption was more favourable

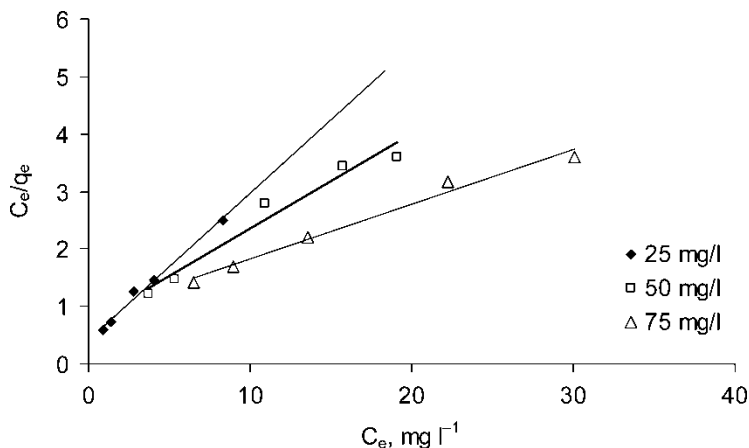


Figure 5. Langmuir isotherm for sorption of Cr^{6+} onto guava seeds ($\text{pH } 1$, $d_p 550 \mu\text{m}$).

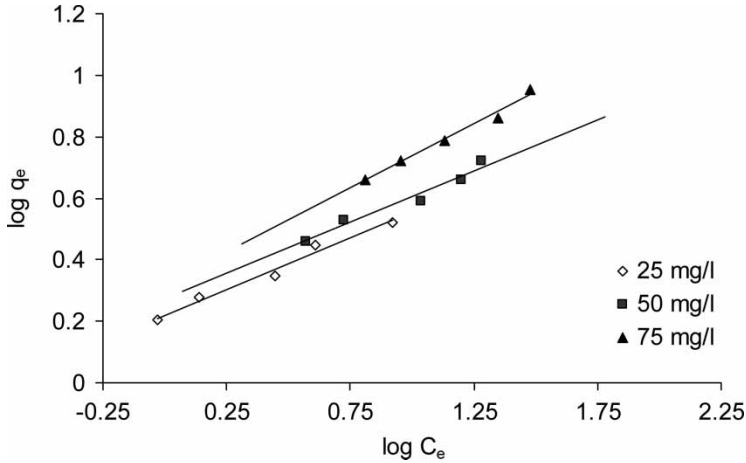


Figure 6. Freundlich isotherm for sorption of Cr^{6+} onto guava seeds (pH 1, d_p 550 μm).

at lower concentrations than at higher concentrations, which is due to the effect of the external mass-transfer coefficient. The Freundlich coefficient, n , for different Cr^{6+} concentrations ranged from 0.22 to 0.32 l g^{-1} , showing also a favourable adsorption of Cr^{6+} on guava seeds (table 4).

The Redlich–Peterson isotherm [27] contains three parameters and incorporates the features of Langmuir and the Freundlich isotherms. The Redlich–Peterson isotherm has a linear dependence on concentration in the numerator and an exponential function in the denominator. It can be described as follows:

$$q_e = \frac{AC_e}{1 + BC_e^g}. \quad (11)$$

It has three isotherm constants, namely, A , B , and g ($0 < g < 1$), which characterize the isotherm. Three isotherm constants were obtained by a general trial-and-error procedure, which is applicable to computer operation using SPSS program version 10.0 for windows (table 4). However, the Langmuir and the Freundlich isotherms seem to be more applicable to our adsorption data obtained by guava seed, since the R^2 values obtained for the Redlich–Peterson isotherm ranged between 0.73 and 0.95.

3.3 Adsorption dynamics

Kinetics of adsorption, in terms of solute uptake rate, which governs the residence time, is one of the important characteristics defining the efficiency of adsorption. The adsorption rate

Table 4. Adsorption isotherm parameters for Cr^{6+} removal at pH 1.0, $d_p = 550 \mu\text{m}$.

Cr^{6+} conc. (mg l^{-1})	Langmuir model			Freundlich model			Redlich–Peterson model			
	K_L (mg g^{-1})	b (l g^{-1})	R^2	K_F (mg g^{-1})	n	R^2	A (l g^{-1})	B	g (l mg^{-1})	R^2
25	3.9	0.62	0.989	2.15	0.22	0.987	2.6	0.28	0.88	0.95
50	6.1	0.23	0.961	2.14	0.27	0.969	1.29	0.09	0.76	0.74
75	10.5	0.11	0.987	2.6	0.32	0.987	1.06	0.04	0.75	0.93

constant is determined from the first-order rate expression given by the Lagergren rate equation [28, 29] as follows:

$$\log(q_e - q_t) = \log q_e - \frac{k_1 \times t}{2.303}, \quad (12)$$

where q_e and q_t are the amounts of Cr adsorbed (mg g^{-1}) at equilibrium and at time t (min), respectively, and k_1 is the rate constant of adsorption (min^{-1}). Values of k_1 were calculated from the plots of $\log(q_e - q_t)$ vs. t for different initial concentrations of Cr^{6+} . The calculated q_e values obtained from the linear plots did not agree with the experimental q_e values. This explained that the adsorption of Cr^{6+} onto guava seeds is not a first-order reaction. The second-order kinetic model [30] is expressed as follows:

$$\frac{t}{q_t} = \frac{1}{(k_2 \times q_e^2)} + \frac{t}{q_e}, \quad (13)$$

where k_2 is the rate constant of second-order adsorption ($\text{g mg}^{-1} \text{min}^{-1}$). If the second-order kinetics is applicable, then the plot of t/q_t vs. t should show a linear relationship (figure 7). The absorption capacity at equilibrium q_e and rate constant k_2 can be calculated from the slope and intercept, respectively. The calculated q_e values showed good agreement with the experimental q_e values with the correlation coefficient ranging from 0.987 to 0.999 (table 5).

Table 6 indicates that a number of sorbents have been used directly for chromium(VI) removal, including activated carbon, cross-linked chitosan, zeolites, sphagnum peat moss, fly ash, and sawdust with a wide range of chromium(VI) sorption capacities. Several natural biosorbents having a cellulose structure have been tested. This work represents a sorption capacity of 10.5 mg g^{-1} , which compares very well with many capacities reported in the literature. Most of the materials in table 6 with a higher chromium sorption capacity are processed sorbents requiring chemicals. Consequently, guava seeds are a low-cost material.

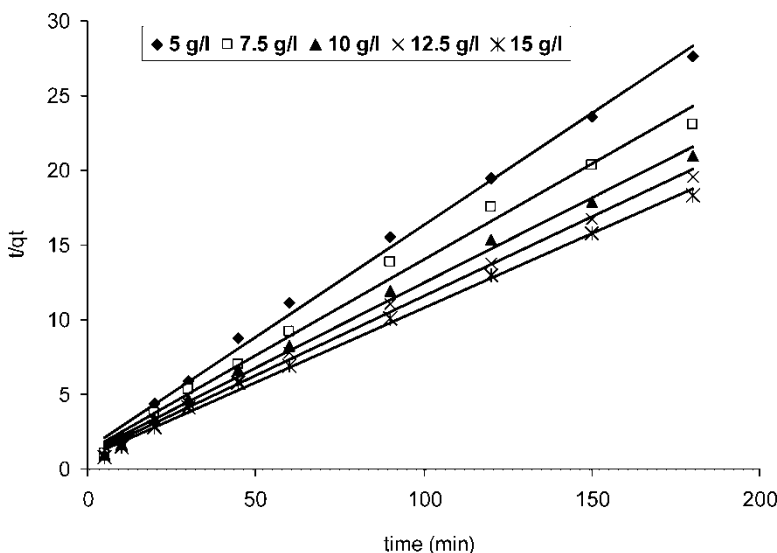


Figure 7. Plot of the pseudo-second-order model for different guava seeds dose using 75 mg l^{-1} initial concentration of chromium at pH 1.0.

Table 5. Comparison of first- and second-order adsorption rate constants and calculated and experimental q_e values for different initial Cr^{6+} and guava-seed concentrations.

Guava weight	Parameter		First-order kinetic model			Second-order kinetic model		
	Initial Cr^{6+} conc.	q_e (exp.)	K_1	q_e (calc.)	R^2	K_2	q_e (calc.)	R^2
5 g/L	25	36.42	0.0145	19.33	0.966	0.0018	36.61	0.987
	50	65.12	0.0175	26.61	0.963	0.0017	66.67	0.996
	75	99.43	0.0115	35.16	0.952	0.0010	100.00	0.992
7.5 g/L	25	27.94	0.0235	16.94	0.917	0.0025	30.12	0.992
	50	51.97	0.0115	19.78	0.921	0.0020	52.08	0.992
	75	75.09	0.0150	29.23	0.969	0.0013	78.13	0.995
10 g/L	25	24.69	0.0143	12.77	0.991	0.0029	25.44	0.991
	50	42.90	0.0127	16.05	0.962	0.0024	43.85	0.992
	75	65.16	0.0138	23.89	0.922	0.0017	66.67	0.995
12.5 g/L	25	20.75	0.0131	8.31	0.975	0.0058	20.53	0.998
	50	36.86	0.0164	14.74	0.981	0.0031	37.59	0.996
	75	55.81	0.0164	23.63	0.989	0.0018	57.47	0.996
15 g/L	25	16.67	0.0237	5.56	0.964	0.0105	17.12	0.999
	50	32.67	0.0161	12.38	0.979	0.0036	33.44	0.997
	75	48.13	0.0164	18.13	0.988	0.0025	49.26	0.998

Table 6. Results of other adsorbents used for adsorption of Cr^{6+} collected from literatures.

Material used for adsorption	Capacity (mg g^{-1})	Reference
Activated carbon from <i>Terminalia arjuna</i> nuts	28.43	[23]
Cross linked chitosan	50.0	[31]
Chabazite-phillipsite	7.10	[32]
Jordanian zeolite	0.25	[33]
Sphagnum peat moss	43.9	[34]
Fly ash-wollastonite	2.92	[35]
Fly ash-China clay	0.31	[35]
Activated red mud	1.6	[36]
Blast-furnace slag	7.5	[37]
Saw dust	2.29	[38]
Guava seeds	10.5	Present work

4. Conclusions

The data from batch studies on the biosorption of Cr^{6+} on guava seeds have provided fundamental information in terms of optimum pH and optimum guava-seed dose for maximum removal of chromium from the solution. The aqueous adsorption tests of Cr^{6+} onto guava seeds indicated that the uptake of Cr^{6+} was greatly affected by the initial solution pH, initial Cr^{6+} concentration, and mass of adsorbent material. Adsorption of Cr^{6+} was highly pH-dependent, and the optimum pH was found to be $\cong 1.0$, where Cr exists in the most easily adsorbed form. The maximum chromium removal was found to be $10.5 \times 10^3 \text{ mg Cr}^{6+}$ per kilogram of dry-weight guava seeds at a pH of 1.0 in 180 min with an initial concentration of 75 mg l^{-1} . Increasing the initial Cr^{6+} concentration led to an increase in the rate of adsorption and consequently an increase in the external mass-transfer coefficient and intra-particle diffusion coefficient. The external mass-transfer coefficient and intra-particle mass-transfer diffusion coefficient increase with increasing biomass. The mechanism of adsorption involves an initial rapid rate of Cr^{6+} removal due to surface adsorption followed by intra-particle

diffusion, which suggests that two or more transport phenomena occur successively. The Langmuir and Freundlich models fit the isotherm data well. The data thus obtained may be helpful for designing and establishing a continuous treatment plant for water and wastewaters enriched in Cr^{6+} . The cost of removal is expected to be quite low, as the adsorbent is cheap and easily available in large quantities.

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