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Batch Study of Liquid-Phase Adsorption of Lead Ions Using Lalang (*Imperata cylindrica*) Leaf Powder

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Abstract: A batch adsorption method was applied to study the adsorption of Pb²⁺ ions from aqueous solution by lalang or *Imperata cylindrica* (IC) leaf powder. Effect of initial lead concentration, contact time, pH of solution, temperature and adsorbent dose were also investigated. A strong dependence of adsorption capacity on pH was observed as the capacity increased with increasing pH. Adsorption equilibrium was established in about 120 min. Adsorption of lead was found to increase with increasing temperature indicating endothermic nature of adsorption. The kinetic data were analyzed using various kinetic models particularly pseudo-first-order, pseudo-second-order, Ritchie's-second-order, Elovich and intraparticle diffusion equations. Results show that the pseudo-second order kinetic model was found to agree well with the experimental data. Equilibrium isotherm data were tested using three models-Langmuir, Freundlich and Temkin. Equilibrium data agreed well with Langmuir model. The maximum adsorption capacity of lead by IC leaf powder determined from Langmuir model was 5.89 mg g⁻¹ at pH 4.

Key words: Adsorption, *Imperata cylindrica*, kinetic, isotherm

INTRODUCTION

The presence of heavy metals in the environment poses a serious and complex pollution problem that has become a major attention by scientists all over the world. Lead is one of the toxic heavy metals widely discharged into the environment as industrial waste in many developing countries, causing serious soil and water pollution. Lead has been known to pollute the environment by waste streams, which originates from metallurgical industry, electroplating and metal finishing industries, paint manufacture, storage battery manufacture, petroleum refining and drainage from ore mines. Excessive exposure to lead may lead to anemia, mental retardation, coma, seizures and bizarre behavior (Botkin and Keller, 2000). Numerous methods have been introduced for removing lead from wastewaters mainly chemical precipitation, chemical oxidation or reduction, ultrafiltration, electrochemical treatment, reverse osmosis, phytoextraction, electrodialysis, application of membrane technology, evaporation recovery, solvent extraction and ion exchange processes. However, the aforementioned techniques are very expensive, may produce large volume of wastes and not economically feasible for small and medium industries (Volesky, 1990; Aksu, 2005). Adsorption processes using natural adsorbents or

agricultural waste products are becoming the new alternative for wastewater treatment because they are cheap, simple, sludge free and involve small initial cost and land investment. Some of the examples of adsorbent materials that have been applied for the removal of lead from aqueous solutions are given in Table 1. In this research, the effectiveness of adsorption of lead ions by IC leaf powder was studied. IC has been ranked as one of the ten worst weeds of the world (Holm *et al.*, 1977). It is

Table 1: Categories of adsorbent material successfully tested for the removal of lead from wastewaters

Adsorbent category	Q _{max} (mg g ⁻¹)	Reference
Agriculture by-product		
ZnO-loading granular activated carbon (coconut shell)	76.59	Kikuchi <i>et al.</i> (2006)
Rubber leaf powder	46.73	Hanafiah <i>et al.</i> (2006b)
Sago waste	46.6	Quek <i>et al.</i> (1998)
Spent grain	35.5	Low <i>et al.</i> (2000)
Chinese herb Pang Da Hai	27.1	Liu <i>et al.</i> (2006)
Coconut shell (activated carbon)	26.50	Sekar <i>et al.</i> (2004)
<i>Pinus sylvestris</i> sawdust	22.22	Taty-Costodes <i>et al.</i> (2005)
Granular activated carbon (coconut shell)	10.76	Kikuchi <i>et al.</i> (2006)
Rice husk ash	12.61	Feng <i>et al.</i> (2004)
Cocoa shells	6.23	Meunier <i>et al.</i> (2003)
Maple sawdust	3.19	Yu <i>et al.</i> (2001)
Cedar bark	3.17	Meunier <i>et al.</i> (2002)
Microorganism		
<i>Phellinus badius</i> (fungi)	170	Matheickal and Yu (1997)

Table 1: Continued

Adsorbent Category	Q _{max} (mg g ⁻¹)	Reference
<i>Phanerochaete chrysosporium</i> (fungal biomass)	135.3	Iqbal and Edyvean (2004)
<i>Zoogloea ramigera</i> (activated sludge bacterium)	94.71	Sağ and Kutsal (1995)
<i>Bacillus</i> sp. (bacterial strain)	92.27	Tunali <i>et al.</i> (2006)
<i>Aspergillus niger</i> (fungus)	35.92	Dursun (2006)
<i>Phomopsis</i> sp. (filamentous fungus)	0.68	Saiano <i>et al.</i> (2005)
Mineral		
Clinoptilolite	166	Bektas and Kara (2004)
Activated phosphate	155.04	Mouflih <i>et al.</i> (2005)
Natural bentonite	14.50	Donat <i>et al.</i> (2005)
Siderite	14.06	Erdem and Ozverdi (2005)
Aquatic plant/waste		
Sea nodule residues	99.0	Agrawal <i>et al.</i> (2005)
<i>Ceratophyllum demersum</i>	44.8	Keskinkan <i>et al.</i> (2004)
<i>Myriophyllum spicatum</i>	46.49	Keskinkan <i>et al.</i> (2003)
Reed (<i>Phragmites australis</i>)	17.2	Southicak <i>et al.</i> (2006)
Industrial waste		
Bagasse fly ash	2.50	Gupta and Ali (2004)
sugar industry waste		
Biopolymer		
Chitosan nanoparticles	398	Qi and Xu (2004)
Chitosan beads	35.21	Ngah <i>et al.</i> (2002)
Chitosan flakes	7.72	Ngah <i>et al.</i> (2002)
Advanced material		
Carbon nanotubes	16.14	Li <i>et al.</i> (2005)

widely distributed in Africa, Asia, Australia and America. This species is considered a pernicious pest plant due its ability to successfully colonize, spread and subsequently compete and displace desirable vegetation and disrupt ecosystems (Holm *et al.*, 1977). This study determines the parameters that influence adsorption of lead such as pH of the solution, temperature, initial lead concentration, contact time and adsorbent dose. The kinetic or rate of adsorption based on pseudo-first-order, pseudo-second-order, Ritchie's-second-order, Elovich and intraparticle diffusion equations were also studied.

MATERIALS AND METHODS

Preparation of adsorbent: IC leaves were collected from the surrounding area of Universiti Teknologi MARA, Pahang campus, Malaysia. The leaves were extensively washed with distilled water to remove dirt, dried in an oven at 105°C for a period of 24 h, then ground and screened to obtain the average particle size of 355 µm. The powder was preserved in glass bottles for use as adsorbent.

Adsorption experiments: All the chemicals used in the experiments were of analytical grade reagents. Pb (NO₃)₂ (Merck) was used as the source of Pb²⁺ and all of the solutions were made in distilled water. The solutions of Pb²⁺ were prepared from a stock solution containing 1000 mg L⁻¹ of Pb²⁺. In general, batch adsorption

experiments were carried out in a series of Erlenmeyer flasks of 100 mL capacity by agitating 0.1 g (unless otherwise stated) of the adsorbent with 25 mL of the aqueous Pb²⁺ solution in a constant temperature (30°C), water bath shaker (Mettmert, Germany) for a pre-determined time interval at a constant speed of 150 rpm. The initial pH of the solution was fixed at 4 by adding drops of 0.1 M HCl or NaOH solutions. For isotherm study, 0.1 g of adsorbent was mixed with 25 mL lead solutions at various concentrations (5-100 mg L⁻¹) and the mixtures were shaken for 120 min (equilibrium time). The effect of pH on lead adsorption was performed at pH range 2-5, using a lead concentration of 20 mg L⁻¹. The study on the effect of temperature was carried out at two different temperatures, 30 and 40°C. After adsorption, the mixture was filtered through Whatman filter paper (No. 40). The concentrations of lead in the solutions before and after equilibrium were determined by atomic absorption spectrophotometer (Perkin Elmer, Analyst 400) using air-acetylene flame. All experiments were performed in duplicates and results are reported as average.

Metal uptake: The amount of Pb²⁺ adsorbed, q_t (mg g⁻¹) was computed by using the following expression:

$$q_t = \frac{C_0 - C_t}{m} V \quad (1)$$

where C₀ and C_t are Pb²⁺ concentrations in mg L⁻¹ before and after adsorption at time t, V is the volume of adsorbate in liter (L) and m is the weight of the adsorbent in gram (g).

FTIR analysis: The FTIR spectrum of IC leaf powder was recorded with JASCO (Japan) FTIR Spectrophotometer. Samples of 200 mg KBr and 2 mg IC leaf powder were prepared and subjected to analysis.

RESULTS AND DISCUSSION

FTIR spectrum: FTIR analysis was carried out in order to identify the functional groups in the IC leaf powder that might be involved in the adsorption process. The FTIR spectrum in the range of 400-4000 cm⁻¹ is shown in Fig. 1. As shown in the figure, the spectrum displays a number of absorption peaks, which indicates the complex nature of the material examined. The broad and strong band ranging from 3000 to 3600 cm⁻¹ may be due to the overlapping of OH and NH stretching, which is consistent with the peak at 1047 and 1162 cm⁻¹ assigned to alcoholic C-O and C-N stretching vibration. The absorption band

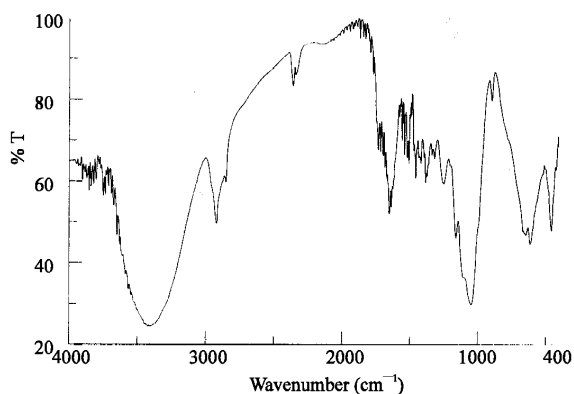


Fig. 1: FTIR spectrum of IC leaf powder

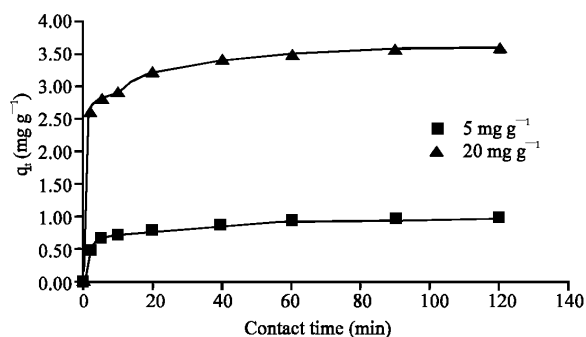


Fig. 2: Effect of initial lead concentration and contact time on lead adsorption onto IC leaf powder

Table 2: FTIR spectrum of IC leaf powder

Frequency (cm ⁻¹)	Assignment
3000-3600	-OH and -NH stretching
2920	-CH stretching
2851	-CH ₂ stretching
1630	C=O stretching in carbonyl or amide
1246	-SO ₂ stretching
1161	-CN stretching
1047	-C-O stretching of alcoholic groups

wave numbers of 2920 and 2851 cm⁻¹ can be assigned to CH and-CH₂ stretching, respectively. The absorption band wave number of the amide group is about 1630 cm⁻¹. Table 2 shows the infrared absorption frequencies of each peak and the corresponding functional groups of IC leaf powder.

Adsorption kinetic: Adsorption kinetic, which describes the adsorbate adsorption rate, is an important characteristic in evaluating the efficiency of adsorption. The adsorption data at different initial Pb²⁺ concentrations is shown in Fig. 2. The plots show that kinetic of adsorption of Pb²⁺ consisted of two phases; an initial rapid phase where adsorption was fast and a second slower phase where equilibrium uptake was achieved. The

first phase is related to external surface adsorption of lead, which occurs instantaneously. The second phase is the gradual adsorption stage before the lead uptake reaches equilibrium. The time to reach equilibrium is 120 min and the maximum amounts of Pb²⁺ adsorbed are 0.979 and 3.594 mg g⁻¹ for lead concentrations of 5 and 20 mg L⁻¹, respectively. According to Bhattacharyya and Gupta (2006), the initial high rate of metal uptake may be attributed to the existence of the bare surface. The number of available adsorption sites decreased as the number of Pb²⁺ ions adsorbed increases. The enhanced adsorption of metal ion with increase in agitation time may also be due to the decrease in boundary layer resistance to mass transfer in the bulk solution and an increase in the kinetic energy of hydrated ions (Horsfall and Abia, 2003). By increasing the agitation time, the boundary layer resistance will be reduced, but the mobility of ions in the solution will increase. For the following experiments, the contact time was maintained for 120 min to ensure that equilibrium was really achieved.

Identifying the slowest step or rate-determining step is also crucial in any kinetic study. In order to investigate the controlling mechanisms of adsorption processes, the pseudo-first-order (Ho and McKay, 1998), pseudo-second-order (Ho, 1995), Elovich (Chien and Clayton, 1980), Ritchie's-second-order (Ritchie, 1977) and intraparticle diffusion (Weber and Morris, 1963) rate equations were used to test the experimental data. The pseudo-first-order kinetic model is given as:

$$\log (q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \quad (2)$$

where q_t and q_e are the amount adsorbed (mg g⁻¹) at time t and at equilibrium and k_1 is the rate constant of the pseudo-first-order adsorption process (min⁻¹). Straight-line plots of $\log (q_e - q_t)$ against t were used to determine the rate constants, k_1 and correlation coefficients, R^2 for different lead concentrations.

The pseudo-second-order equation is expressed as:

$$\frac{1}{q_t} = \frac{1}{h} + \frac{1}{q_e} t \quad (3)$$

where $h = kq_e^2$ can be regarded as the initial sorption rate as $t \rightarrow 0$ and k is the rate constant of second-order adsorption (g mg⁻¹ min⁻¹). The plot t/q_t versus t should give a straight line if second-order kinetic is applicable and q_e , k and h can be determined from the slope and intercept of the plot, respectively. The plots of the linearized form of the pseudo-first-order and pseudo-

Table 3: Comparison between adsorption rate constants, q_e estimated and coefficients of correlation associated to the pseudo-first-order and to the pseudo-second-order kinetic models

[Pb] (mg L ⁻¹)	Pseudo-first-order kinetic model			Pseudo-second-order kinetic model				
	k_1 (min ⁻¹)	q_e (mg g ⁻¹)	R^2	k (g mg ⁻¹ min ⁻¹)	q_e (mg g ⁻¹)	R^2	h (mg g ⁻¹ min ⁻¹)	$q_{e,exp}$ (mg g ⁻¹)
5	0.0336	0.397	0.9622	0.338	0.990	0.9982	0.331	0.978
20	0.0380	0.943	0.9961	0.177	3.619	0.9996	2.313	3.594

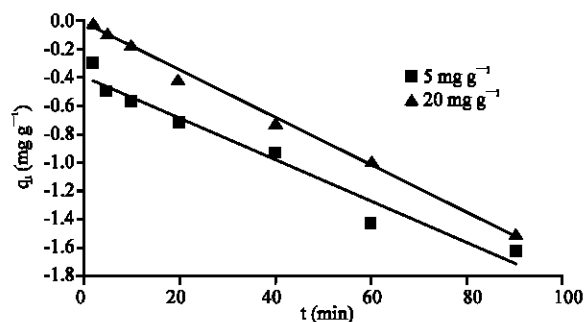


Fig. 3: Pseudo-first-order plots for lead adsorption onto IC leaf powder

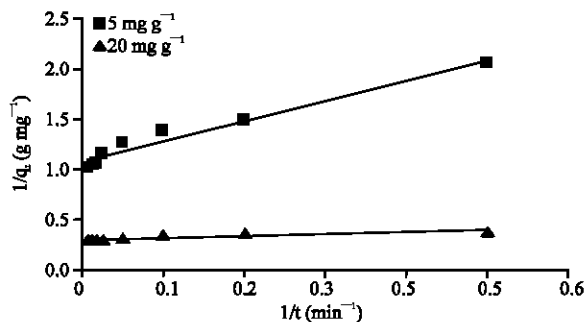


Fig. 5: Ritchie's second-order plots for lead adsorption onto IC leaf powder

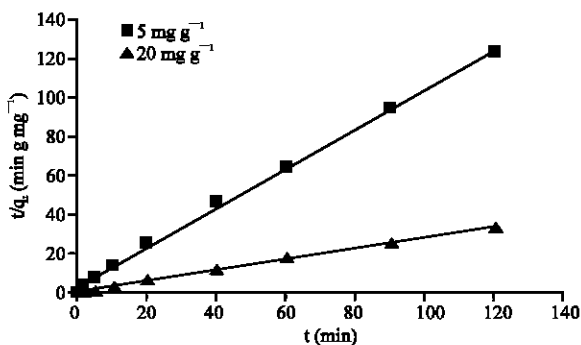


Fig. 4: Pseudo-second-order plots for lead adsorption onto IC leaf powder

second-order model at different Pb²⁺ concentrations by IC leaf powder are shown in Fig. 3 and 4, respectively.

The pseudo-first-order rate constants (k_1) and q_e determined from Eq. 2 are presented in Table 3 along with the corresponding correlation coefficients. The rate constants, calculated from the slopes of the best-fit lines were in the range of 3.36×10^{-2} to 3.38×10^{-2} min⁻² for pseudo-first order model. The dependence of the first-order rate constant with concentration and the coefficients of correlation were lower than those found for the pseudo-second-order model. It can be observed in this study that q_e values computed from the experiment did not agree with q_e values obtained from pseudo-first-order plots. This indicates that pseudo-first-order kinetic might not be sufficient to describe the mechanism of Pb²⁺–IC interactions.

The plot of t/q_t versus t for pseudo-second-order model (Fig. 4) yields very good straight lines (correlation

coefficient, $R^2 > 0.99$). The pseudo-second-order rate constants were in the range of 1.77×10^{-1} to 3.38×10^{-1} g mg⁻¹ min⁻¹, as shown in Table 3. The theoretical values of q_e also agree very well with the experimental ones. Both facts suggest that the adsorption of Pb²⁺ ions by IC leaf powder follows the pseudo-second-order kinetic model. This finding was similar to other studies on the adsorption of lead by low-cost adsorbents. For instance, pseudo-second-order kinetic was also observed in the adsorption of cadmium and lead by spent grain (Low *et al.*, 2000), adsorption of cadmium and lead onto *Hevea brasiliensis* leaf powder (Hanafiah *et al.*, 2006a,b) and adsorption of lead onto activated carbon prepared from coconut shell (Sekar *et al.*, 2004).

Ritchie's second-order equation based on adsorption equilibrium capacity is expressed in the form:

$$\frac{1}{q_t} = \frac{1}{k_2 q_e t} + \frac{1}{q_e} \quad (4)$$

where k_2 is the rate constant of the second-order adsorption. From Eq. 4, a plot of $1/q_t$ versus $1/t$ should give a straight line (Fig. 5) and the rate constants (k_2) and adsorption at equilibrium (q_e) can be determined from the slope and intercept, respectively. The theoretical values of q_e obtained from Ritchie second-order plots were found to be lower than those of the experimental values. The summary of q_e and k_2 values determined from Ritchie second-order are given in Table 4.

The Elovich equation has been applied satisfactorily to some chemisorption processes and the equation is

Table 4: Parameters for Ritchie second-order and Elovich equations

[Pb] (mg L ⁻¹)	Ritchie second-order			Elovich			
	k ₂ (g mg ⁻¹ min ⁻¹)	q _e (mg g ⁻¹)	R ²	α (mg g ⁻¹ min ⁻¹)	β (g mg ⁻¹)	R ²	q _{e,exp} (mg g ⁻¹)
5	0.549	0.922	0.958	0.1211	8.696	0.9798	0.978
20	1.467	3.411	0.7757	3763.1	3.962	0.9841	3.594

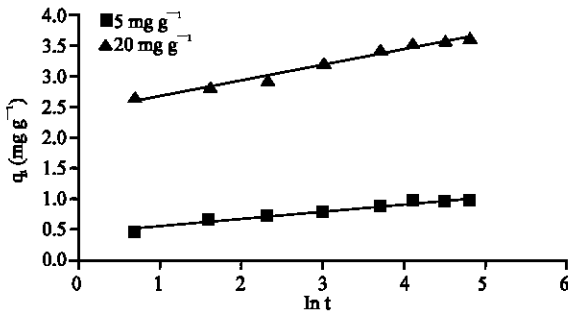


Fig. 6: Elovich plots for lead adsorption onto IC leaf powder

often valid for systems in which the adsorbing surface is heterogeneous. The Elovich equation is generally express as:

$$\frac{dq_t}{dt} = \alpha e^{-\beta q_t} \quad (5)$$

where α is the initial adsorption rate (mg g⁻¹ min⁻¹), β is the desorption constant (g mg⁻¹). To simplify the Elovich equation, Chien and Clayton (1980) assumed $\alpha\beta t \gg 1$ and by applying the boundary conditions $q_t = 0$ at $t = 0$ and $q_t = q_e$ at $t = t$, Eq. 5 becomes:

$$q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln t \quad (6)$$

If lead adsorption fits the Elovich model, a plot of q_t versus $\ln t$ should give a linear relationship with a slope of $1/\beta$ and an intercept of $1/\beta \ln \alpha\beta$. The Elovich plots for lead adsorption at two different concentrations are shown in Fig. 6. Table 4 lists the kinetic constants obtained from Elovich equation for two different lead concentrations. It can be seen that on increasing the lead concentration, the value of α increases from 0.121 to 3763.1 mg g⁻¹ min⁻¹.

The intraparticle diffusion equation is given as:

$$q_t = k_{id} t^{1/2} \quad (7)$$

where k_{id} (mg g⁻¹ min^{-1/2}) is the intraparticle rate constant and can be obtained from the slope of the second portion of the straight-line of plot q_t versus $t^{1/2}$ (Fig. 7). As can be seen from Fig. 7, the adsorption was controlled by three different stages: the first sharper portion being a rapid external surface adsorption, the second linear portion

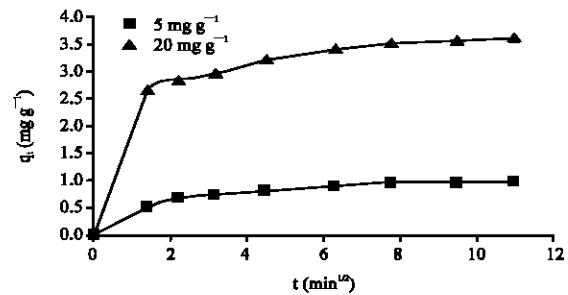


Fig. 7: Intraparticle diffusion plots for lead adsorption onto IC leaf powder

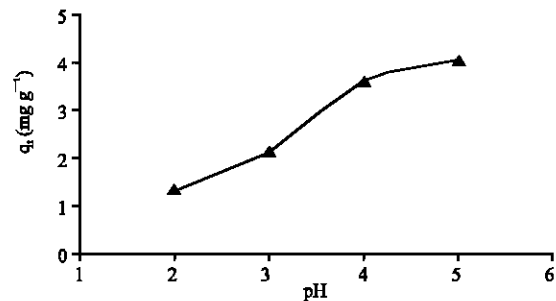


Fig. 8: Effect of pH on lead adsorption onto IC leaf powder

being a gradual adsorption where intraparticle diffusion is the rate limiting factor and the final portion being final equilibrium stage due to low concentration of lead in solution phase as well as less number of available adsorption sites. It is obvious that intraparticle diffusion is not the sole rate-determining step as the second portions of plots of q_t versus $t^{1/2}$ did not have zero intercept (Ho and McKay, 2003). The values of k_{id} were 4.83×10^{-2} and 1.36×10^{-1} mg g⁻¹ min^{-1/2} for lead concentrations of 5 and 20 mg g⁻¹, respectively.

Effect of pH: pH is an important parameter for adsorption process due to its influence on the ionization state of the functional groups on the surface of adsorbent (carboxylate, hydroxy, etc) and different ionic forms of lead. According to Sekar *et al.* (2004), above pH 5.5, lead starts to precipitate as Pb(OH)₂. Therefore experiments were performed in the pH range 2-5. As can be seen in Fig. 8, the adsorption of Pb²⁺ ions from aqueous solution is mainly influenced by solution pH. It is noticed that adsorption increased continuously with the decrease in

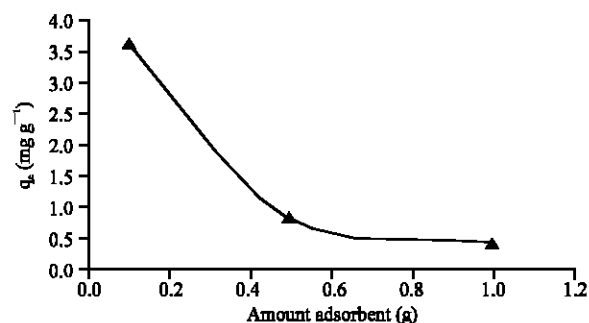


Fig. 9: Effect of adsorbent dose on lead adsorption onto IC leaf powder

Table 5: Amount of lead removed (%) and adsorbed (mg g⁻¹) at three different adsorbent doses

Amount of adsorbent (g)	Removal (%)	Lead adsorbed (mg g ⁻¹)
0.1	71.9	3.59
0.5	83.0	0.83
1.0	86.0	0.43

acidity until it reached maximum adsorption capacity at pH 5. The increase in lead adsorbed as pH increases can be explained on the basis of a decrease in competition between proton (H⁺) and lead ions on the surface of adsorbent. As pH increased, more adsorbent surface would be exposed and carried negative charges, with subsequent attraction of lead ions (Brady and Duncan, 1994).

Effect of adsorbent dose: The dependence of adsorption of lead on the amount of IC was studied at room temperature (30°C) at pH 4.0 by varying the adsorbent doses from 0.10 to 1.0 g while keeping the volume (25 mL) and concentration of the metal solution constant. The result is shown in Fig. 9 and Table 5. The percent lead removal from the solution is seen to increase with increasing adsorbent dose. The percent removal of Pb(II) ions increased from 71.9 to 86.0 for adsorbent dose of 0.10 and 1.0 g, respectively. According to Shukla *et al.* (2002), the decrease in adsorption density (mg g⁻¹) with increase in adsorbent dose is due to the high number of unsaturated adsorption sites.

Effect of temperature: The effect of temperature on lead adsorption for lead concentration of 20 mg L⁻¹ is shown in Fig. 10 and Table 6. It is found that the amount of lead adsorbed increased with increasing temperature, indicating endothermic nature of adsorption. A similar finding was also observed by Dursun (2006) for the biosorption of Cu(II) and Pb(II) ions onto pretreated *Aspergillus niger*. At equilibrium, the amount of lead adsorbed were 3.59 and 4.07 mg g⁻¹ at temperatures 30 and 40°C, respectively. At higher temperature (40°C), the

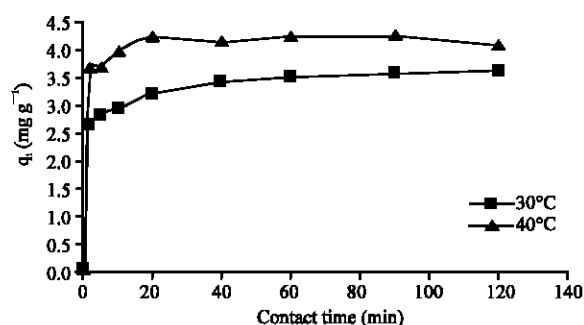


Fig. 10: Effect of temperature on lead adsorption onto IC leaf powder

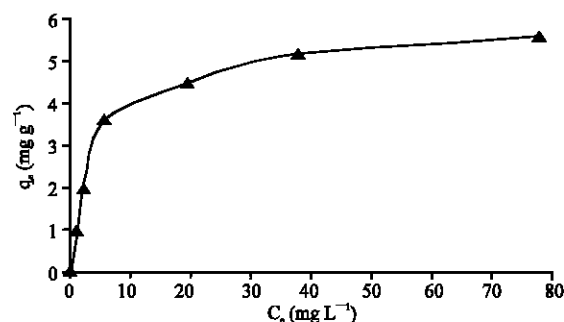


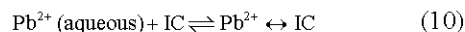
Fig. 11: Adsorption isotherm plot for lead adsorption onto IC leaf powder

time taken for adsorption to reach equilibrium was much shorter (20 min). The Gibbs free energy (ΔG) for lead adsorption was calculated using the following equations:

$$K_c = \frac{C_{Ae}}{C_e} \quad (8)$$

$$\Delta G = -RT \ln K_c \quad (9)$$

where K_c is the equilibrium constant (unitless), C_e is the equilibrium concentration in solution (mg L⁻¹) and C_{Ae} is the solid-phase concentration at equilibrium (mg L⁻¹). Spontaneity of the adsorption process was demonstrated by the increase in Gibbs energy, ΔG (values varied from -2.363 kJ mol⁻¹ at 30°C to -3.851 kJ mol⁻¹ at 40°C) as shown in Table 6. The negative values of ΔG indicate that the equilibrium:



shifts to the forward direction in a spontaneous manner leading to binding of Pb²⁺ ions on to surface constituents of IC leaf powder. The increase in lead adsorbed with temperature could be due to changes in the pore size, desolvation of the adsorbate and the increase in the rate of intraparticle diffusion (Sekar *et al.*, 2004).

Table 6: Comparison of ΔG values at two different temperatures for Pb(II) adsorption onto IC leaf powder

[Pb] mg L ⁻¹	T = 30°C			T = 40°C		
	q _e (mg g ⁻¹)	K _L	ΔG (kJ mol ⁻¹)	q _e (mg g ⁻¹)	K _L	ΔG (kJ mol ⁻¹)
20	3.59	2.556	- 2.363	4.07	4.394	- 3.851

Table 7: Langmuir, Freundlich and Temkin adsorption isotherms for removal of Pb²⁺ ions onto IC leaf powder

Langmuir constants			Freundlich constants			Temkin constant		
Q _{max} (mg g ⁻¹)	b (L mg ⁻¹)	R ²	n	K _F (mg g ⁻¹)	R ²	b _{Te} (J mol ⁻¹)	K _T (L mg ⁻¹)	R ²
5.89	0.208	0.9989	2.669	1.339	0.8689	2362.7	3.181	0.9709

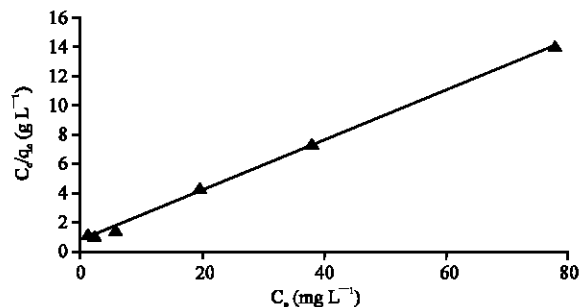


Fig. 12: Langmuir plot for lead adsorption onto IC leaf powder

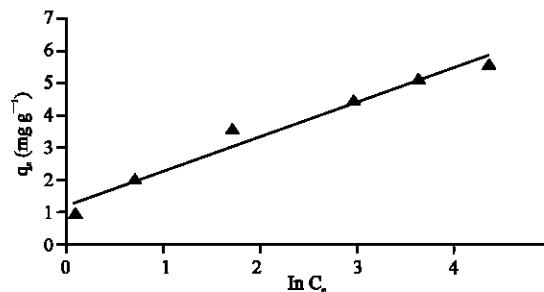


Fig. 14: Temkin plot for lead adsorption onto IC leaf powder

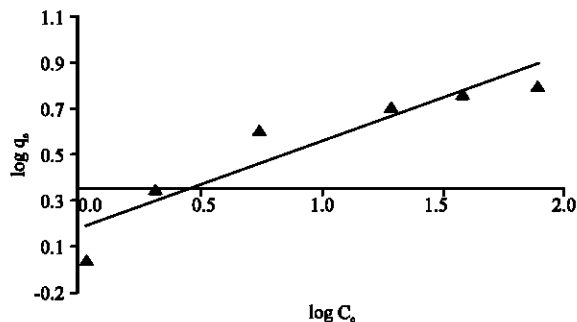


Fig. 13: Freundlich plot for lead adsorption onto IC leaf powder

Adsorption isotherms: The maximum adsorption capacity of IC leaf powder for lead was investigated over a range of lead concentrations. Figure 11 shows the plot of the adsorption capacity, q_e (mg g⁻¹) versus the equilibrium concentration of lead ions in the solution, C_e (mg L⁻¹). The amount of lead adsorbed was found to increase with increasing lead concentration until the maximum adsorption capacity was achieved.

The distribution of metal ions between liquid and solid phases is generally described by using the Langmuir (1916), Freundlich (1906) and Temkin and Pyzheh (1940) adsorption isotherm models. The Langmuir model assumes uniform energies of adsorption onto the adsorbent surface and no transmigration of adsorbate in the plane of the surface. The Freundlich isotherm model however is applicable to highly heterogeneous surface. The Langmuir and Freundlich adsorption isotherms are given as:

$$\frac{C_e}{q_e} = \frac{1}{Q_{\max} b} + \frac{C_e}{Q_{\max}} \quad (11)$$

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (12)$$

where, C_e is the equilibrium Pb²⁺ concentration (mg L⁻¹), q_e the amount of Pb²⁺ adsorbed at equilibrium (mg g⁻¹) and Q_{\max} , b , K_F and n are the isotherm constants. Q_{\max} and K_F are defined as maximum adsorption capacity (mg g⁻¹) for Langmuir and Freundlich isotherms, respectively. Figure 12 and 13 show the Langmuir and Freundlich adsorption isotherms obtained by plotting C_e/q_e versus C_e and $\log q_e$ versus $\log C_e$, respectively. According to Mohanty *et al.* (2006), if the value of n is greater than 1, it indicates favorable adsorption of metal ions on the surface of adsorbent. The value of n determined from Freundlich isotherm was 2.669 as shown in Table 7, indicating that Pb(II) ions are favorably adsorbed by IC leaf powder.

Temkin isotherm model is given as;

$$q_e = \frac{RT}{b_{Te}} \ln K_T + \frac{RT}{b_{Te}} \ln C_e \quad (13)$$

where T is the temperature (°K), R is the universal gas constant, 8.314 J mol⁻¹, K_T is the equilibrium constant (L mg⁻¹) and b_{Te} is related to the heat of adsorption (J mol⁻¹). According to Aharoni and Ungarish (1977), the derivation of Temkin isotherm assumes that the fall in the heat of adsorption is linear rather than logarithmic, as

implied in the Freundlich equation. Temkin plot is shown in Fig. 14 and the values of K_T and b_{Te} are given in Table 7. Based on the R^2 values obtained from the three adsorption isotherm models, it is clear that the Langmuir has best fitted for the adsorption of lead onto IC leaf powder. The maximum adsorption capacity determined from the Langmuir model was found to be 5.89 mg g^{-1} , as shown in Table 7.

CONCLUSIONS

This study indicates that IC leaf powder has rapid adsorption rate and good adsorption capacity for lead. The Pb^{2+} adsorption was found to be dependent on initial lead concentration, contact time, pH, temperature and adsorbent dose. The adsorption of lead fitted the Langmuir isotherm model, which suggests monolayer coverage of adsorbent surface. Kinetic of lead adsorption however obeyed the pseudo-second order model, which suggests chemisorption as the rate-determining step in adsorption process. Maximum adsorption of lead occurred at pH 5 and a higher adsorption rate occurred at higher temperature, indicating endothermic nature of adsorption. Since IC leaves are highly abundant and can be easily synthesized at relatively low cost, the adsorbent could be applied for the removal of lead from wastewaters.

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