Journal of Biological Sciences

ISSN 1727-3048
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, electrodeposition, 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>
<thead>
<tr>
<th>Adsorbent category</th>
<th>Q_{max} (mg g⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Agriculture by-product</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc-loading granular activated carbon (coconut shell)</td>
<td>76.59</td>
<td>Kikuchi <em>et al.</em> (2006)</td>
</tr>
<tr>
<td>Rubber leaf powder</td>
<td>46.73</td>
<td>Hanafiah <em>et al.</em> (2006b)</td>
</tr>
<tr>
<td>Sugarcane waste</td>
<td>46.6</td>
<td>Quck <em>et al.</em> (1998)</td>
</tr>
<tr>
<td>Spent grain</td>
<td>35.5</td>
<td>Low <em>et al.</em> (2000)</td>
</tr>
<tr>
<td>Chinese herb Pang Da Hai</td>
<td>27.1</td>
<td>Liu <em>et al.</em> (2008)</td>
</tr>
<tr>
<td>Pinus sylvestris sawdust</td>
<td>22.22</td>
<td>Tity-Costodes <em>et al.</em> (2005)</td>
</tr>
<tr>
<td>Granular activated carbon (coconut shell)</td>
<td>10.76</td>
<td>Kikuchi <em>et al.</em> (2006)</td>
</tr>
<tr>
<td>Rice husk ash</td>
<td>12.61</td>
<td>Feng <em>et al.</em> (2004)</td>
</tr>
<tr>
<td>Coconuts shells</td>
<td>6.23</td>
<td>Meunier <em>et al.</em> (2005)</td>
</tr>
<tr>
<td>Maple sawdust</td>
<td>3.19</td>
<td>Yu <em>et al.</em> (2001)</td>
</tr>
<tr>
<td>Cedar bark</td>
<td>3.17</td>
<td>Meunier <em>et al.</em> (2002)</td>
</tr>
<tr>
<td><strong>Microorganism</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phellinus radiatus (fungi)</td>
<td>170</td>
<td>Matheickal and Yu (1997)</td>
</tr>
</tbody>
</table>

**Corresponding Author:** M.A.K. Megat Hanafiah, Faculty of Applied Sciences, Universiti Teknologi MARA Pahang, 26400, Jengka, Pahang, Malaysia Tel: +609-4602322 Fax: +609-4602455
Table 1: Continued

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>$Q_{eq}$ (mg g$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phaeosphaeria chryssoptorium</td>
<td>135.3</td>
<td>Iqbal and Eddyvean (2004)</td>
</tr>
<tr>
<td>(fungal biomass)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zoogloea ramigera (activated</td>
<td>94.71</td>
<td>Sag and Katsal (1995)</td>
</tr>
<tr>
<td>sludge bacteria)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacillus sp. (bacterial strain)</td>
<td>92.27</td>
<td>Tunali et al. (2006)</td>
</tr>
<tr>
<td>Aspergillus niger (fungus)</td>
<td>35.92</td>
<td>Dursun (2006)</td>
</tr>
<tr>
<td>Phenomys sp. (filamentous fungus)</td>
<td>0.68</td>
<td>Saisuo et al. (2005)</td>
</tr>
<tr>
<td><em>Mineral</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlinoilolite</td>
<td>166</td>
<td>Bektas and Kara (2004)</td>
</tr>
<tr>
<td>Activated phosphate</td>
<td>155.64</td>
<td>Mouflikh et al. (2005)</td>
</tr>
<tr>
<td>Natural bentonite</td>
<td>14.50</td>
<td>Donat et al. (2005)</td>
</tr>
<tr>
<td>Siderite</td>
<td>14.06</td>
<td>Erdem and Ozverdi (2005)</td>
</tr>
<tr>
<td><em>Aquatic plant/waste</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea nodule residues</td>
<td>99.0</td>
<td>Agrawal et al. (2005)</td>
</tr>
<tr>
<td>Ceratothrix dolomica</td>
<td>44.8</td>
<td>Keskin et al. (2004)</td>
</tr>
<tr>
<td>Myriophyllum spicatum</td>
<td>46.49</td>
<td>Keskin et al. (2003)</td>
</tr>
<tr>
<td>Reed (Phragmites australis)</td>
<td>17.2</td>
<td>Southcatt et al. (2006)</td>
</tr>
<tr>
<td><em>Industrial waste</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar industry waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biopolymer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chitosan nanoparticles</td>
<td>398</td>
<td>Qi and Xu (2004)</td>
</tr>
<tr>
<td>Chitosan beads</td>
<td>35.21</td>
<td>Ngah et al. (2002)</td>
</tr>
<tr>
<td>Chitosan flakes</td>
<td>7.77</td>
<td>Ngah et al. (2002)</td>
</tr>
<tr>
<td><em>Advanced material</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon nanotubes</td>
<td>16.14</td>
<td>Li et al. (2005)</td>
</tr>
</tbody>
</table>

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(NO$_3$)$_2$ (Merck) was used as the source of Pb$^{2+}$ and all of the solutions were made in distilled water. The solutions of Pb$^{2+}$ were prepared from a stock solution containing 1000 mg L$^{-1}$ of Pb$^{2+}$. 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 Pb$^{2+}$ solution in a constant temperature (30°C), water bath shaker (Mmemert, Germany) for a predetermined 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, Aanalyst 400) using air-acetylene flame. All experiments were performed in duplicates and results are reported as average.

**Metal uptake**: The amount of Pb$^{2+}$ adsorbed, $q_e$ (mg g$^{-1}$) was computed by using the following expression:

$$q_e = \frac{C_0 - C_1 \times V}{m}$$

where $C_0$ and $C_1$ are Pb$^{2+}$ concentrations in mg L$^{-1}$ before and after adsorption at time t, $V$ is the volume of the 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
wave numbers of 2920 and 2851 cm\(^{-1}\) can be assigned to-CH and-CH\(_2\) 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 Pb\(^{2+}\) concentrations is shown in Fig. 2. The plots show that kinetic of adsorption of Pb\(^{2+}\) 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 Pb\(^{2+}\) 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 Pb\(^{2+}\) 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:

\[
\log (q_e - q_t) = \log q_e - \frac{k_1 t}{2.303}.
\]

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:

\[
\frac{1}{q_t} = \frac{1}{h} + \frac{1}{q_e} \frac{1}{k}\frac{1}{t}
\]

where \(h = \frac{kq_e^2}{2}\) can be regarded as the initial sorption rate as \(t \to 0\) 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

<table>
<thead>
<tr>
<th>[Pb] (mg L$^{-1}$)</th>
<th>Pseudo-first-order kinetic model</th>
<th>Pseudo-second-order kinetic model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_1$ (min$^{-1}$)</td>
<td>$q_e$ (mg g$^{-1}$)</td>
</tr>
<tr>
<td>5</td>
<td>0.0336</td>
<td>0.397</td>
</tr>
<tr>
<td>20</td>
<td>0.0380</td>
<td>0.943</td>
</tr>
</tbody>
</table>

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

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

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

second-order model at different Pb$^{2+}$ 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 $3.36 \times 10^{-2}$ to $3.38 \times 10^{-2}$ min$^{-1}$ 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 Pb$^{2+}$-IC interactions.

The plot of $t/q_e$ 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 $1.77 \times 10^{-1}$ to $3.38 \times 10^{-1}$ 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 Pb$^{2+}$ 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 (Haranafiah 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:

$$
\frac{1}{q_e} = \frac{1}{k_2 q_i} + \frac{1}{q_e}
$$

where $k_2$ is the rate constant of the second-order adsorption. From Eq. 4, a plot of $1/q_e$ 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

<table>
<thead>
<tr>
<th>[Pb] (mg L⁻¹)</th>
<th>Ritchie second-order</th>
<th>Elovich</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k₂ (g mg⁻¹ min⁻¹)</td>
<td>qₑ (mg g⁻¹)</td>
</tr>
<tr>
<td>5</td>
<td>0.549</td>
<td>0.922</td>
</tr>
<tr>
<td>20</td>
<td>1.467</td>
<td>3.411</td>
</tr>
</tbody>
</table>

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:

\[
\frac{dq}{dt} = \alpha e^{-\beta t}
\]  

(5)

where \( \alpha \) is the initial adsorption rate (mg g⁻¹ min⁻¹), \( \beta \) is the desorption constant (g mg⁻¹). To simplify the Elovich equation, Chien and Clayton (1980) assumed \( \alpha \beta t >> 1 \) and by applying the boundary conditions \( q = 0 \) at \( t = 0 \) and \( q_0 = q \) at \( t = t \), Eq. 5 becomes:

\[
q = \frac{1}{\beta} \ln(\alpha \beta t) + \frac{1}{\beta} \ln t
\]  

(6)

If lead adsorption fits the Elovich model, a plot of \( q \) 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 \( \alpha \) increases from 0.121 to 3765.1 mg g⁻¹ min⁻¹.

The intraparticle diffusion equation is given as:

\[
q = k_d t^{1/2}
\]  

(7)

where \( k_d \) (mg g⁻¹ min⁻¹) is the intraparticle rate constant and can be obtained from the slope of the second portion of the straight-line of plot \( q \) 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 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 \( q \) versus \( t^{1/2} \) did not have zero intercept (Ho and McKay, 2003). The values of \( k_d \) were \( 4.83 \times 10^{-3} \) and \( 1.36 \times 10^{-4} \) mg g⁻¹ min⁻¹ 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 iconic 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
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 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:

\[
K_c = \frac{C_s}{C_i}
\]

\[
\Delta G = -RT \ln K_c
\]

where \(K_c\) is the equilibrium constant (unitless), \(C_s\) is the equilibrium concentration in solution (mg L⁻¹) and \(C_{ic}\) 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:

\[
Pb^{2+} (\text{aqueous}) + IC \rightleftharpoons PbIC
\]

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

<table>
<thead>
<tr>
<th>[Pb] mg L⁻¹</th>
<th>q (mg g⁻¹)</th>
<th>( K_r )</th>
<th>ΔG (kJ mol⁻¹)</th>
<th>q (mg g⁻¹)</th>
<th>( K_r )</th>
<th>ΔG (kJ mol⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.59</td>
<td>2.556</td>
<td>2.565</td>
<td>4.07</td>
<td>4.394</td>
<td>3.853</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Langmuir constants</th>
<th>Freundlich constants</th>
<th>Temkin constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{max} ) (mg g⁻¹)</td>
<td>( b ) (L mg⁻¹)</td>
<td>( R^2 )</td>
</tr>
<tr>
<td>5.89</td>
<td>0.208</td>
<td>0.9989</td>
</tr>
</tbody>
</table>

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

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

\[ \frac{C_e}{q_e} = \frac{1}{Q_{max} b} + \frac{C_e}{Q_{max}} \]  

(11)

\[ \log q_e = \log K_r + \frac{1}{n} \log C_e \]  

(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 \( Q_{max}, b, K_r \) and \( n \) are the isotherm constants. \( Q_{max} \) and \( K_r \) 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:

\[ q_e = \frac{RT}{b_r} \ln K_r + \frac{RT}{b_r} \ln C_e \]  

(13)

where \( T \) is the temperature (°K), \( R \) is the universal gas constant, 8.314 J mol⁻¹ K⁻¹, \( K_r \) is the equilibrium constant (L mg⁻¹) and \( b_r \) is related to the heat of adsorption (J mol⁻¹). According to Aharoni and Ungarisch (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 $b_T$ 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.

ACKNOWLEDGMENT

The authors thank the Institute of Research, Development and Commercialization (IRDC), Universiti Teknologi MARA for the financial support.

REFERENCES


