SORPTION STUDIES OF LEAD IONS ONTO ACTIVATED CARBON PRODUCED FROM OIL-PALM FRUIT FIBRE.

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ABSTRACT

The batch sorption removal of Pb^{2+} from aqueous solution using treated oil palm fruit fibre was studied. The adsorption equilibrium and kinetic studies of Pb^{2+} on such fibre were then examined at 25°C. Adsorption isotherm of Pb^{2+} on the activated carbon produced from treated oil palm fibre was determined and correlated with common isotherm equations. The equilibrium data for Pb^{2+} adsorption fitted well to the Langmuir equation with maximum monolayer adsorption capacity of 588.24 mg/g. The batch sorption model, based on a pseudo-second-order mechanism, was applied to predict the rate constant of sorption, the equilibrium capacity and the initial sorption rate with the effects of the initial solution pH and fiber dose. The adsorption capacity at equilibrium increases from 75.48 to 439.06 mg g^{-1} with an increase in the initial lead concentration from 100 to 500 mg l^{-1}. Equilibrium concentrations were evaluated with the equilibrium capacity obtained from the pseudo-second-order rate equation.

Keywords: Oil palm fruit fibre; Adsorption; Isotherm; Kinetics.

1.0. Introduction

The use of activated carbon to remove heavy metal ions from wastewater by adsorption is a well-established process. The economics of this process depends mainly on the cost of the adsorbent material. As such, low cost adsorbents are becoming the focus of many investigations. Low cost adsorbents could be produced from many raw materials such as agriculture and industrial wastes. On the use of low cost adsorbents in the removal of dyes, we have investigated the adsorption of methylene blue onto activated carbon derived from periwinkle shells in recent time (Bello et al. 2008). In Nigeria, the palm oil industry generates huge amounts of palm shell. Some of this solid waste is usually used as fuel to produce process steam and/or electricity in palm oil mills. However, a large portion of it is either burned in open air or dumped in areas adjacent to the mill, which creates huge environmental and disposal problems. In recent years, the interest to palm shell has increased mainly due to the fact that this material was shown to be an excellent source of high quality and low cost activated carbon. However, most of the research on palm shell carbon is focused on the processes of carbonization and activation (Hussein et al. 1996, Lua and Guo 1998, Guo 2002, Daud et al. 2002, Daud and Ali 2004). Application of palm shell activated carbon as an adsorbent offers highly effective technological means dealing with heavy metal pollution of the aqua-environment with minimum investment requirements. The adsorption of cadmium and lead on the modified oil palm shell was investigated (Othman et al. 1994). The capacity of activated carbons obtained from the different parts of oil palm and the modified palm shell activated carbon to remove phenols from wastewaters has also been investigated (Abu Bakar 1999, Salim et al. 2002). The application of palm oil fuel ash in the removal of chromium and zinc from aqueous solutions has been reported (Chu and Hashim 2002a, b). Information on the performance of oil palm fiber based activated carbon for the adsorption of heavy metals from aqueous solutions is scanty. The advantage of using inexpensive natural resource as raw materials for manufacturing activated carbon is that these raw materials are renewable and potentially less expensive to manufacture. The aim of the present study is to explore the use of activated carbon produced from oil palm fibre for the removal of Pb^{2+} from aqueous solution. It is also aimed to determine which isotherm and model fit the adsorption process most.

2.0. Materials and Methods.

2.1. Preparation and characterization of adsorbent

The oil palm fruit fibre was obtained from a local oil palm mill in YOACO Area, Ogbomoso, Oyo State, Nigeria. The fibre collected was deoiled by soaking it in hot deionized water and with detergent for 24 hours. It was rinsed thoroughly in hot deionized water to remove all debris and then air dried. The air dried oil palm fruit fibre was grounded using a medium size mortal and pestle. The pretreated material was then carbonized at 700°C under nitrogen atmosphere for 1 h (first pyrolysis). A certain amount of produced char was then soaked with potassium hydroxide (KOH) at impregnation ratio of 1:1 (KOH pellets: char). The mixture was dehydrated in an oven overnight at 105°C; then pyrolysed in a stainless steel vertical tubular reactor placed in a tube furnace under high purity nitrogen (99.995%) flow of 150 $cm^3 min^{-1}$ (second pyrolysis) to a final temperature of 850°C and activated for 2 h. Once the final temperature was reached, the gas flow was switched to carbon dioxide and activation was continued for 2 h. The activated product was then cooled to room temperature under nitrogen flow and washed with deionised water to remove the remaining chemical. Subsequently, the sample was transferred to a beaker containing a 250 ml solution of hydrochloric acid (about 0.1 mol l^{-1}), stirred for 1 h, and then washed with hot deionised water until the pH of the washing solution reached 6 –7. Textural characterization of the activated carbon (AC) was carried out by N_2 adsorption at 77K using Autosorb I, supplied by Quantachrome Corporation, USA. The BET (N_2, 77K) is the most usual standard procedure used when characterizing an activated carbon (Sing *et al.*, 1985). It was found that the BET surface area, total pore volume, average pore diameter and pH point of zero charge (pHpzc) of the activated carbon were 1654m^2 g^{-1}, 1.115 cm^3 g^{-1}, 2.54 nm and 8.0, respectively. The pH point of zero charge (pHpzc) of activated carbon prepared from oil palm fibre shows that there exists a relationship between pHpzc and adsorption capacity of the adsorbent used. The result shows that cation adsorption will be favourable at pH value higher than pHpzc. While anion adsorption will be favoured at pH values lower than their adsorbent pHpzc (Nomanbhay and Palanisamy, 2005).

The treated oil palm fibre sample (10 mg) was ground with 200 mg of KBr (spectroscopic grade) in a mortar pressed into 10 mm diameter disks under 10 tonnes of pressure and high vacuum for 10 min. FTIR spectra were obtained on a JASCO FTIR-3500 spectrometer. The analysis conditions used were 16 scans at a resolution of 4 cm^{-1} measured between 400 and 4000 cm^{-1}. The FTIR spectra of oil palm fibre, treated oil palm fibre and the oil palm fibre after adsorption are shown in Fig. 1. The FTIR spectra of oil palm fibre showed peaks at 3240, 3015, 1650, 1540, 1450, 1420 1250 and 1160 cm^{-1} which may be assigned to OH group, aliphatic C–H group, unsaturated groups like alkene, amide, CH deformation, OH deformation, aromaticity and OH stretch, respectively. The intensity of the peaks were either minimized or shifted slightly in case of treated and adsorbed oil palm fibre, respectively. These results are similar to the ones reported for sawdust (Huang et al. 2005).

2.2. Preparation of lead nitrate solution

All the reagents used were of analytical grade and doubly deionized water was used in sample preparation. 1000 mg l^{-1} stock solution of Pb^{2+} was prepared from $Pb(NO_3)_2$. From the stock solution, working solutions with different initial concentrations (ranging from 100 to 500 mg l^{-1}) were prepared by serial dilution.

2.3. Batch equilibrium studies

Adsorption isotherms were performed in a set of 30 Erlenmeyer flasks (250 ml) where solutions of lead (200 ml) with different initial concentrations (100–500 mg l^{-1}) were placed in these flasks. Equal mass of 0.2 g of particle size (225 µm) activated carbon produced from treated oil palm fibre was added to lead solutions and kept in an isothermal shaker (25 ± 1^0C) for 48 h to reach equilibrium of the solid-solution mixture. Similar procedure was followed for another set of Erlenmeyer flask containing the same lead concentration without activated carbon to be used as a control. The pH was adjusted to 7 by adding either few drops of diluted hydrochloric acid or sodium hydroxide (0.1 mol l^{-1}). The flasks were then removed from the shaker and the final concentration of lead in the solution was analyzed using atomic absorption spectrophotometer.

The samples were filtered prior to analysis in order to minimize interference of the carbon fines with the analysis. Each experiment was duplicated under identical conditions. The amount of adsorption at equilibrium, q_e (mg g^{-1}), was calculated by

$$q_e = \frac{(C_o - C_e)V}{W} \text{……………………………………} (1)$$

where C_o and C_e (mg l^{-1}) are the liquid-phase concentrations of lead at initial and equilibrium, respectively. V is the volume of the solution (litre), and W is the mass of dry adsorbent used (g).

2.4. Batch kinetic studies

The procedures of kinetic experiments were basically identical to those of equilibrium tests. The aqueous samples were taken at preset time intervals, and the concentrations of lead were similarly measured. The amount of adsorption at time *t*, q_t (mg g^{-1}),was calculated by:

$$q_t = \frac{(C_o - C_t)V}{W} \quad \text{………………………………. (2)}$$

where C_o and C_t (mg l^{-1}) are the liquid-phase concentrations of lead at initial and any time *t*, respectively. V is the volume of the solution (litre), and W is the mass of dry adsorbent used (g).

2.5. Adsorption dynamics

The order of a reaction and rate constant must be determined by experiments. A pseudo-second-order rate law expression was applied, which demonstrated how the rate depended on the sorption capacity but not the concentration of the sorbate (Ho and McKay 2000). Oil palm fibre, a cellulose-based sorbent, contains polar functional groups that can be involved in chemical bonding and are responsible for the cation exchange capacity of the oil palm fibre. Thus, the oil palm fibre and lead reaction may be represented in two ways (Ho and McKay 1998, 1999 and 2000).

$$2F^{-} + Pb^{2+} \leftrightarrow PbF_2 \quad \text{…………………………………………………….. (3)}$$

and

$$2HF + Pb^{2+} \leftrightarrow PbF_2 + 2H^{+} \quad \text{………………………………………… (4)}$$

where F^- and HF are polar sites on the oil palm fibre surface. The rate of sorption to the surface should be proportional to a driving force times an area. The rate of the pseudo-second-order reaction may be dependent on the amount of solute sorbed on the surface of the oil palm fibre at any time and the amount sorbed at equilibrium. The rate expression for the sorption described is:

$$\frac{dF_t}{dt} = k[F_e - F_t]^2 \quad \text{……………………………………………….. (5)}$$

$$\frac{d[HF]_t}{dt} = k[(HF)_e - (HF)_t]^2; \quad \text{………………………………… (6)}$$

where F_t and $(HF)_t$ are the number of active sites occupied on the oil palm fibre at any time t, and F_e and $(HF)_e$ are the number of equilibrium sites available on the oil palm fibre. The driving force is related to $q_e - q_t$. Thus, the kinetic rate equations can be rewritten as follows:

$$\frac{dq_t}{dt} = k(q_e - q_t)^2; \quad \text{……………………………………………… (7)}$$

where k is the rate constant of sorption (g/(mg min)), q_e the amount of lead ions sorbed at equilibrium (mg/g), and q_t is the amount of lead ions sorbed on the surface of the oil palm fibre at any time t (mg/g). Separating the variables in the equation above gives:

$$\frac{dq_t}{(q_e - q_t)^2} = k\,dt; \quad \text{…………………………………………… (8)}$$

and integrating this for the boundary conditions $t = 0 - t$ and $q_t = 0 - q_t$ gives:

$$\frac{1}{q_e - q_t} = \frac{1}{q_e} + kt \quad \text{………………………………………… (9)}$$

which is the integrated rate law for a pseudo-second-order reaction. This and Eq. (9) can be rearranged to obtain:

$$q_t = \frac{t}{(1/kq_e^2) + (t/q_e)} \quad \text{……………………………… (10)}$$

which has a linear form:

$$\frac{t}{q_t} = \frac{1}{kq_e^2} + \frac{1}{q_e}t \quad \text{……………………………………… (11)}$$

or

$$\frac{q_t}{t} = \frac{h}{1 + kq_e t}; \quad \text{……………………............................ (12)}$$

where h can be regarded as the initial sorption rate as q_t/t, when t approaches 0. Hence,

$$h = kq_e^2. \quad \text{………………………………………………….. (13)}$$

Thus, a plot of t/q_t against t of Eq. (9) should give a linear relationship with a slope of $1/q_e$ and an intercept of $1/kq_e^2$. In order to investigate the mechanism of the sorption of lead ions onto oil palm fibre, a pseudo-second-order mechanism was studied. For the sorption of metal ions, which are small compared with dye molecules, and with a short contact time to equilibrium, the pseudo-second-order kinetic expression was considered likely to be more appropriate (Ho et al. 2000).

3.0 Results and Discussion

3.1. Effect of agitation time and concentration of lead on adsorption.

A series of contact time experiments for lead was carried out at different initial concentrations (100–500 mg l^{-1}) and at temperature of 25^0C. Fig. 2 shows the contact time necessary for lead with initial concentrations of 100–300 mg l^{-1} to reach equilibrium is 6 h. However, for lead with higher initial concentrations (400–500 mg l^{-1}), longer equilibrium time of 24 h is needed. As can be seen from Fig. 2, the amount of the adsorbed lead onto activated carbon produced from treated oil palm fibre increases with time and, at some point in time, reaches a constant value beyond which no more is removed from solution. At this point, the amount of the lead desorbing from the adsorbent is in a state of dynamic equilibrium with the amount of the lead being adsorbed onto the activated carbon. The time required to attain this state of equilibrium is termed the equilibrium time, and the amount of lead adsorbed at the equilibrium time reflects the maximum adsorption capacity of the adsorbent under those operating conditions. The adsorption capacity at equilibrium increases from 75.48 to 439.06 mg g^{-1} with an increase in the initial lead concentration from 100 to 500 mg l^{-1}. It is evident that the activated carbon produced from treated oil palm fibre is efficient in adsorbing lead from aqueous solution, the process attaining equilibrium gradually.

3.2. Adsorption kinetics

The rate constant of adsorption is determined from the pseudo first-order equation given by Langergren and Svenska (Lagergren and Svenska 1898):

$$\ln (q_\mathrm{e} - q_t) = \ln q_\mathrm{e} - k_1 t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

where q_e and q_t are the amounts of lead adsorbed (mg g^{-1}) at equilibrium and at time t (min), respectively, and k_1 the rate constant adsorption (h^{-1}). Values of k_1 were calculated from the plots of ln (q_e -q_t) versus t for different concentrations of lead (Fig. 3). Although the correlation coefficient values at high concentration are higher than 0.90, the experimental q_e values do not agree with the calculated ones, obtained from the linear plots (Table 1). This shows that the adsorption of lead onto activated carbon produced from oil palm fibre is not first-order kinetics.

On the other hand, a pseudo second-order equation based on equilibrium adsorption (Ho and McKay 1998) is expressed as:

$$1/q_t = 1/k_2 q_e^2 + (1/q_t)\, t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

where k_2 (g/mg h) is the rate constant of second-order adsorption. If second-order kinetics is applicable, the plot of t/q versus t should show a linear relationship. There is no need to know any parameter beforehand and q_e and k_2 can be determined from the slope and intercept of the plot. Also, this procedure is more likely to predict the behaviour over the whole range of adsorption. The linear plots of t/q versus t (Fig. 4) show a good agreement between experimental and calculated q_e values (Table 1).

The correlation coefficients for the second-order kinetic model are greater than 0.99 indicating the applicability of this kinetic equation and the second-order nature of the adsorption process of lead on treated oil palm fibre.

3.3. Test of kinetic models

Besides the value of R^2, the applicability of both kinetic models are verified through the sum of error squares (SSE, %). The adsorption kinetics of lead on activated carbon derived from activated carbon produced from oil palm fibre was tested at different initial concentrations. The validity of each model was determined by the sum of error squares (SSE, %) given by:

$$SSE(\%) = \sqrt{\frac{\Sigma(q_e, \exp - q_e, cal)^2}{N}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

where N is the number of data points. The higher is the value of R^2 and the lower is the value of SSE; the better will be the goodness of fit. Table 1 lists the calculated values. It was found that the adsorption of lead on activated carbon produced from oil palm fibre can be best described by the 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) and rubber (*Hevea brasiliensis*) leaf powder (Hanafiah and Ngah 2006, Hanafiah and Shafiei 2006).

3.4. Adsorption isotherms

The adsorption isotherm indicates how the adsorption molecules distribute between the liquid phase and the solid phase when the adsorption process reaches an equilibrium state. The analysis of equilibrium adsorption data by fitting them to different isotherm models is an important step to find the suitable model that can be used for design purpose (Haghseresht and Lu 1998). Adsorption isotherm study is carried out on two well-known isotherms, Langmuir and Freundlich. Langmuir isotherm assumes monolayer adsorption onto a surface containing a finite number of adsorption sites of uniform strategies of adsorption with no transmigration of adsorbate in the plane of surface (Fytianos 2000). While, Freundlich isotherm model assumes heterogeneous surface energies, in which the energy term in Langmuir equation varies as a function of the surface coverage (Weber and Chakkravorti 1974). The applicability of the isotherm equation is compared by judging the correlation coefficients, R^2.

3.5. Langmuir isotherm

The linear form of Langmuir's isotherm model is given by the following equation:

$$C_e/q_e = 1/Q_o b + (1/Q_o)\, C_e \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(17)}$$

where C_e is the equilibrium concentration of the adsorbate (lead) (mg/l), $q_{e,}$ the amount of adsorbate adsorbed per unit mass of adsorbate (mg g^{-1}), and Q_o and b are Langmuir constants related to monolayer adsorption capacity and affinity of adsorbent towards adsorbate, respectively. When C_e/q_e was plotted against C_e, straight line with slope $1/Q_o$ was obtained (Fig.5), indicating that the adsorption of lead on activated carbon produced from activated carbon produced from oil palm fibre follows the Langmuir isotherm. The Langmuir constants 'b' and 'Q_o' were calculated from this isotherm and their values are given in Table 2.

The essential characteristics of the Langmuir isotherm can be expressed in terms of a dimensionless equilibrium parameter (R_L) (Hall et al. 1966, Adamson 2001), which is defined by:

$$R_L = 1/ (1 + bC_0) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (18)$$

where b is the Langmuir constant and C_0 the highest lead concentration (mg l^{-1}). The value of R_L indicates the type of the isotherm to be either unfavorable ($R_L > 1$), linear ($R_L = 1$), favorable ($0 < R_L < 1$) or irreversible ($R_L = 0$). Value of R_L was found to be 0.04 and confirmed that the activated carbon is favorable for adsorption of lead under conditions used in this study.

3.6. Freundlich isotherm

The well-known logarithmic form of Freundlich model is given by the following equation:

$$\log q_e = \log K_F + (1/n) \log C_e \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (19)$$

where q_e is the amount adsorbed at equilibrium (mg g^{-1}), C_e the equilibrium concentration of the adsorbate (lead) and K_F and n are Freundlich constants, n giving an indication of how favorable the adsorption process and K_F (mg g^{-1}(l $mg^{-1})^n$) is the adsorption capacity of the adsorbent. K_F can be defined as the adsorption or distribution coefficient and represents the quantity of lead adsorbed onto activated carbon adsorbent for a unit equilibrium concentration.

The slope $1/n$ ranging between 0 and 1 is a measure of adsorption intensity or surface heterogeneity, becoming more heterogeneous as its value gets closer to zero (Haghseresht and Lu 1998). A value for $1/n$ below one indicates a normal Langmuir isotherm while $1/n$ above one is indicative of cooperative adsorption (Fytianos 2000). The plot of log q_e versus log C_e gives straight lines with slope '$1/n$' (Fig. 6), which shows that the adsorption of lead also follows the Freundlich isotherm. Accordingly, Freundlich constants (K_F and n) were calculated and recorded in Table 2.

Table 2 shows the values of the parameters of the two isotherms and the related correlation coefficients. As seen from Table 2, the Langmuir model yields a somewhat better fit ($R^2 = 0.975$) than the Freundlich model ($R^2 = 0.922$). As also illustrated in Table 2, the value of $1/n$ is 0.466, which indicates favorable adsorption (Adamson 2001).

3.7. Effect of pH

Variations in the amount of lead (II) sorbed as a function of pH was studied, the pH of the lead(II) solution was set to pH 3 – 6, and results are presented in Fig. 7. In this experiment, the agitation speed was 200 rpm, the fiber dose was 1.5 g/dm^3, the initial lead concentration was 120 mg/dm^3. It was observed that there was a rapid increase in the amount of lead sorbed from 2 to 70 % between pH 2 - 4. The percentage sorbed increased slightly to 75 % between pH 4- 5. Thereafter, the amount sorbed remains fairly constant above pH 5. The results obtained were analyzed using the pseudo-second-order model

(Fig.8). The coefficient of determination, R^2, the rate constant, k, the initial sorption rate, h, and the sorption capacity, q_e, were obtained from the slope and intercept of Eq. (11). Individual values are presented in Table 3. The amount of metal ions removal from solution was shown to be strongly affected by the pH of the solution, because it affects the surface charge, degree of ionization and speciation of the metal. The adsorption of lead (II) onto sphagnum moss peat, for example, was found to vary with pH in the range 4 – 6, and the pH of maximum lead (II) uptake was found to be pH 5 (Ho et al, 1996). Srivastava et al. also obtained similar results for lead (II) uptake in the pH range 4 – 6 (Srivastava et al. 1989). In this current study, it is observed that the variation in pH values of the lead (II) solution from pH 2 to 5 produced an increase in sorption capacity from 37.31 to 47.39 mg/g and a corresponding increase in the initial sorption rate. It is also observed that as the pH increased from 5 to 6, the sorption capacity decreased. At a low pH, H^+ ions increase in solution and H^+ ions coordinate with OH groups to form $OH_2{}^+$. This gives the sorbent surface a positive character which leads to repulsion of the positively charged lead (II) from the sorbent surface. The coordination of H^+ ion with OH groups also reduces the cation exchange capacity of the sorbent. At higher pH values, however, the OH groups on the sorbent surface ionize to produce negatively charged oxygen (O^-) which enhances the cation exchange capacity.

3.8. Effect of adsorbent dose

The dependence of adsorption of lead on oil palm fibre was studied at room temperature (25^0C) at pH 4.0 by varying the amount of adsorbent from 0.10 to 1.5 g while keeping the volume (25 ml) and concentration of the lead aqueous solution constant. The result is shown in Fig. 9. The amount of lead adsorbed (mgg^{-1}) was found to decrease with increasing amount of adsorbent. The amount of lead adsorbed decreased from 7.38 to 0.72 for adsorbent amount of 0.10 and 1.5 g, respectively. According to (Shukla *et al.*, 2002), the decrease in adsorption density with increase in adsorbent amount is due to the high number of unsaturated adsorption sites.

4.0 Conclusions

The adsorption of lead onto treated oil palm fibre was investigated in batch experimental system. The following results were obtained:

1. The solution pH played a significant role in influencing the capacity of adsorbents towards the metal ion. An increase in the pH of solution led to a significant increase in the adsorption capacity.
2. The Langmuir isotherm exhibited a little better fit to the lead ion adsorption data by the adsorbent than the Freundlich isotherm.
3. The removal efficiency increased and the adsorption capacity decreased with a rise in adsorbent concentrations.
4. This work has shown that utilization of treated oil palm fibre will be useful in the treatment of lead ion from industrial waste effluents; it will also eliminate various ecological problems these waste effluents could cause.

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Table 1.

Initial concentration (mg^{-1})	$q_{e,exp}$ (mgg^{-1})	First order kinetic model				Second order kinetic model			
		k_1 (h^{-1})	$q_{e,cal}$ (mgg^{-1})	R^2	SSE(%)	k_2 [g(mgh)$^{-1}$]	$q_{e,cal}$ (mgg^{-1})	R^2	SSE(%)
100	75.48	1.562	137.19	0.92	27.60	0.0148	76.92	0.99	0.64
200	189.36	2.726	303.17	0.93	50.90	0.0093	192.31	0.99	1.74
300	282.64	6.680	404.07	0.95	54.31	0.0061	285.71	0.99	1.37
400	375.09	6.880	503.41	0.93	57.39	0.0058	386.62	0.99	5.77
500	439.06	11.243	745.68	0.92	137.12	0.0032	454.55	0.99	6.92

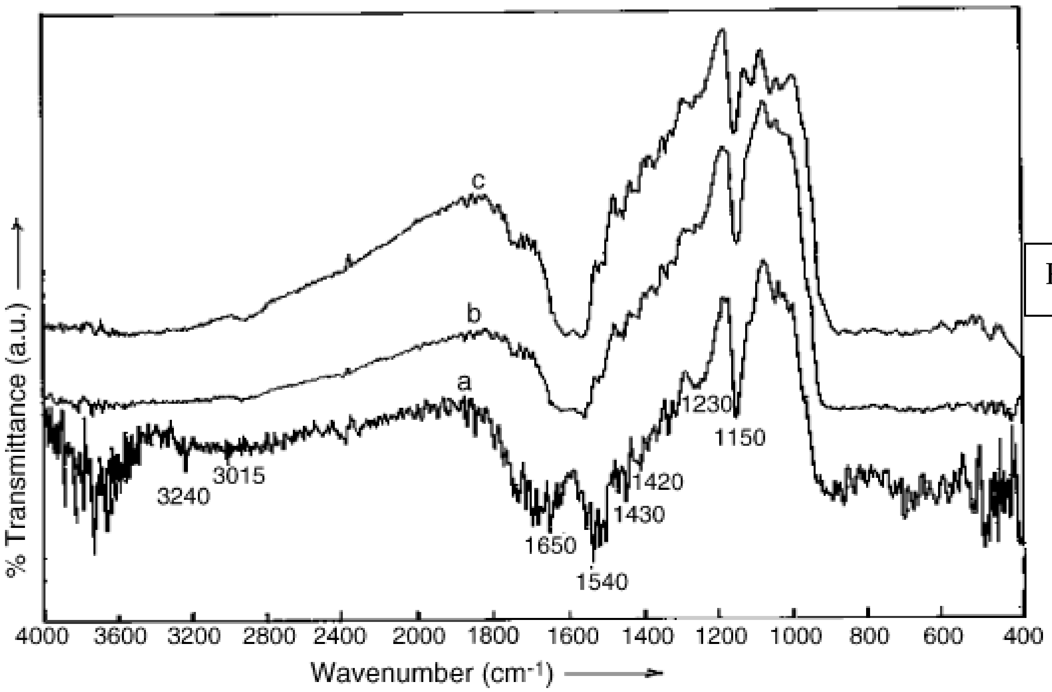
Table 2

Langmuir isotherm	
Q_o (mgg^{-1})	588.24 **± 0.02**
b (L/mg)	0.054 ± **0.03**
R^2	0.975 ± **0.01**
R_L	0.040 ± **0.02**
Freundlich isotherm	
$\frac{1}{n}$	0.466 ± **0.03**
K_F [(mgg^{-1})(mg^{-1})$^{1/n}$]	26.63 ± **0.01**
R^2	0.922 ± **0.02**

All values are means of triplicates ± SD.

Table 3

pH	q_e (mg/g)	k (g/(mg min))	h (mg/(g min)	R^2
2	37.31	0.018	25.06	0.989
3	38.02	0.0318	46.08	0.996
4	42.74	0.0349	63.69	0.997
5	47.39	0.0405	90.19	0.998
6	40.63	0.0415	68.51	0.999



c
b
a
3240
3015
1650
1540
1430
1420
1230
1150
% Transmittance (a.u.)
4000
3600
3200
2800
2400
2000
1800
1600
1400
1200
1000
800
600
400
Wavenumber (cm-1)

Fig 1

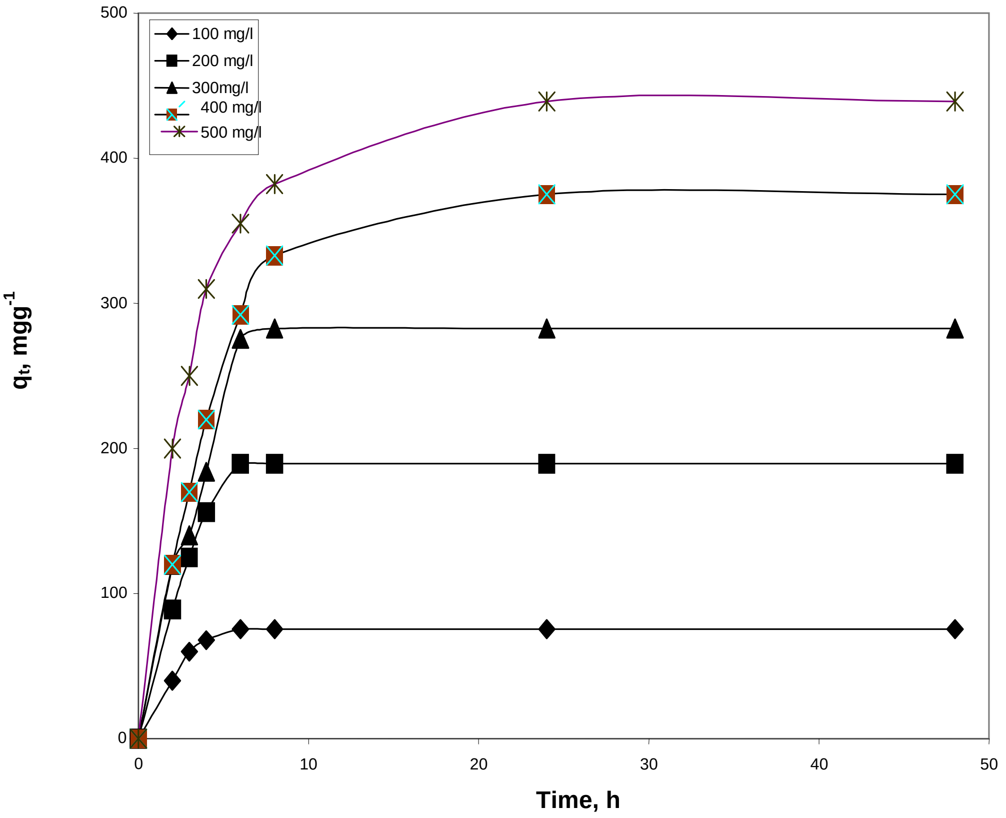

500
400
300
200
100
0
0
10
20
30
40
50
q_t, mgg^{-1}
Time, h
100 mg/l
200 mg/l
300mg/l
400 mg/l
500 mg/l

Fig. 2

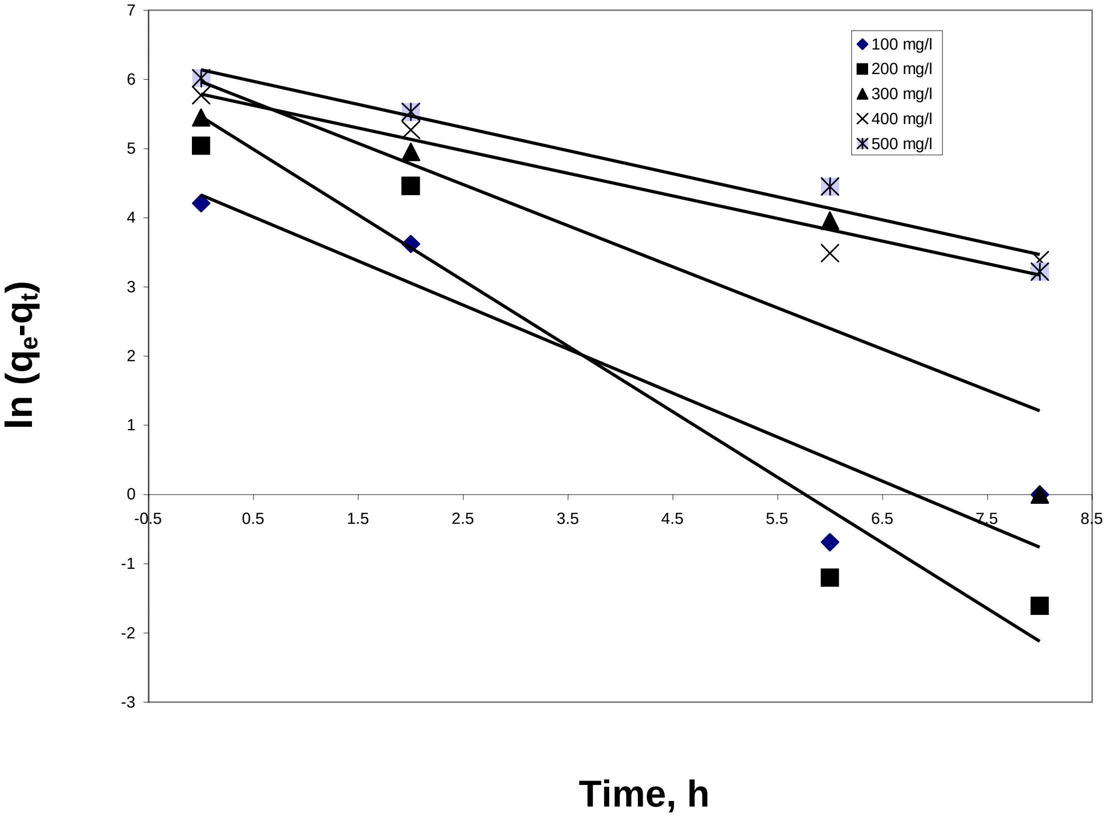
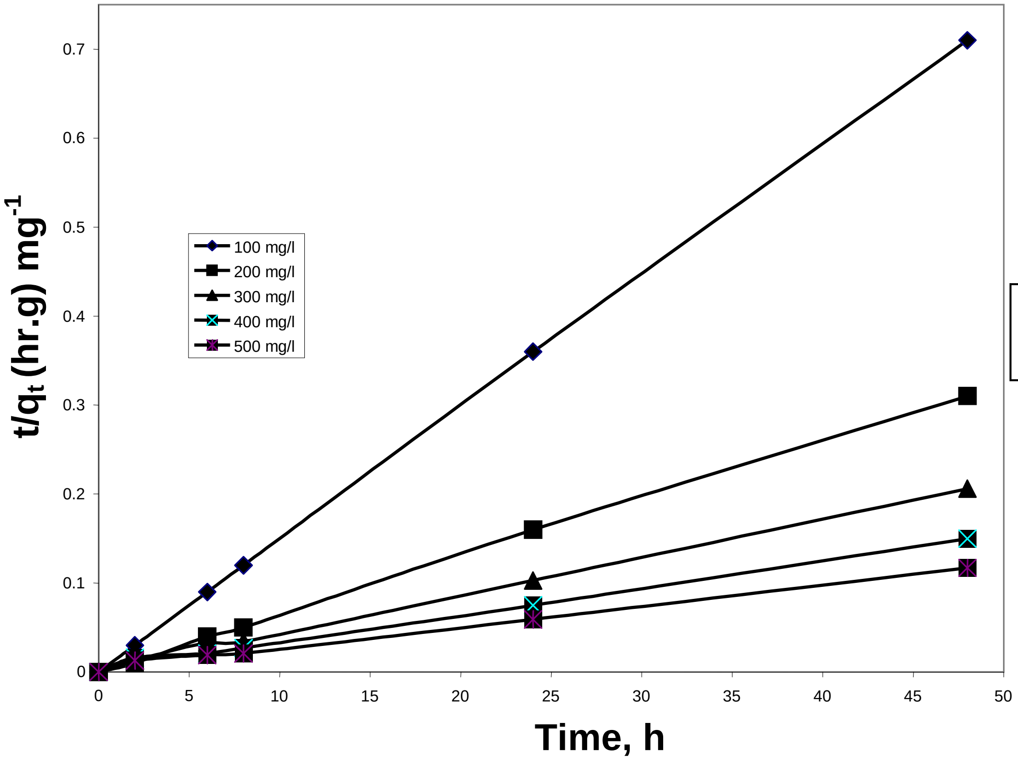

ln (q_e-q_t)
7
6
5
4
3
2
1
0
-1
-2
-3
-0.5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
100 mg/l
200 mg/l
300 mg/l
400 mg/l
500 mg/l
Time, h

Fig 3



t/q_t (hr.g) mg^{-1}
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100 mg/l
200 mg/l
300 mg/l
400 mg/l
500 mg/l
0
5
10
15
20
25
30
35
40
45
50
Time, h

Fig 4

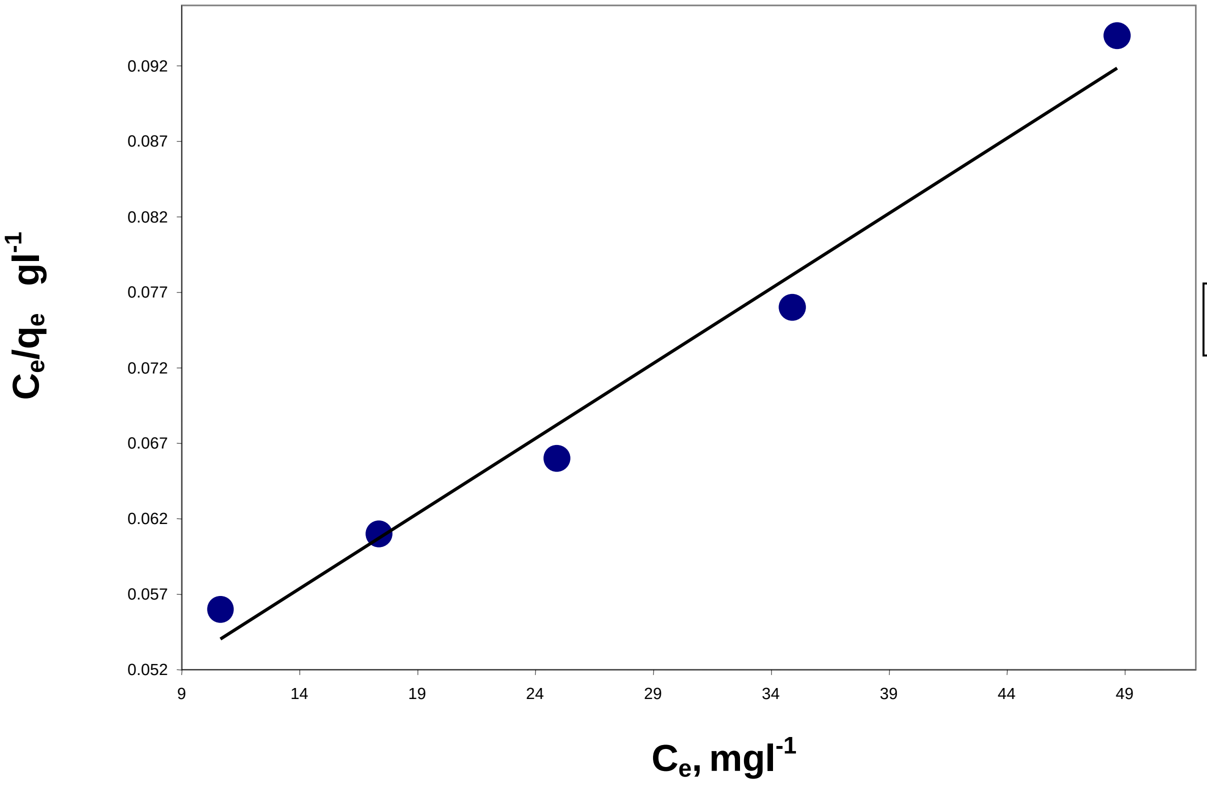

0.092
0.087
0.082
0.077
0.072
0.067
0.062
0.057
0.052
9
14
19
24
29
34
39
44
49
C_e/q_e gl^{-1}
C_e, mgl^{-1}

Fig 5

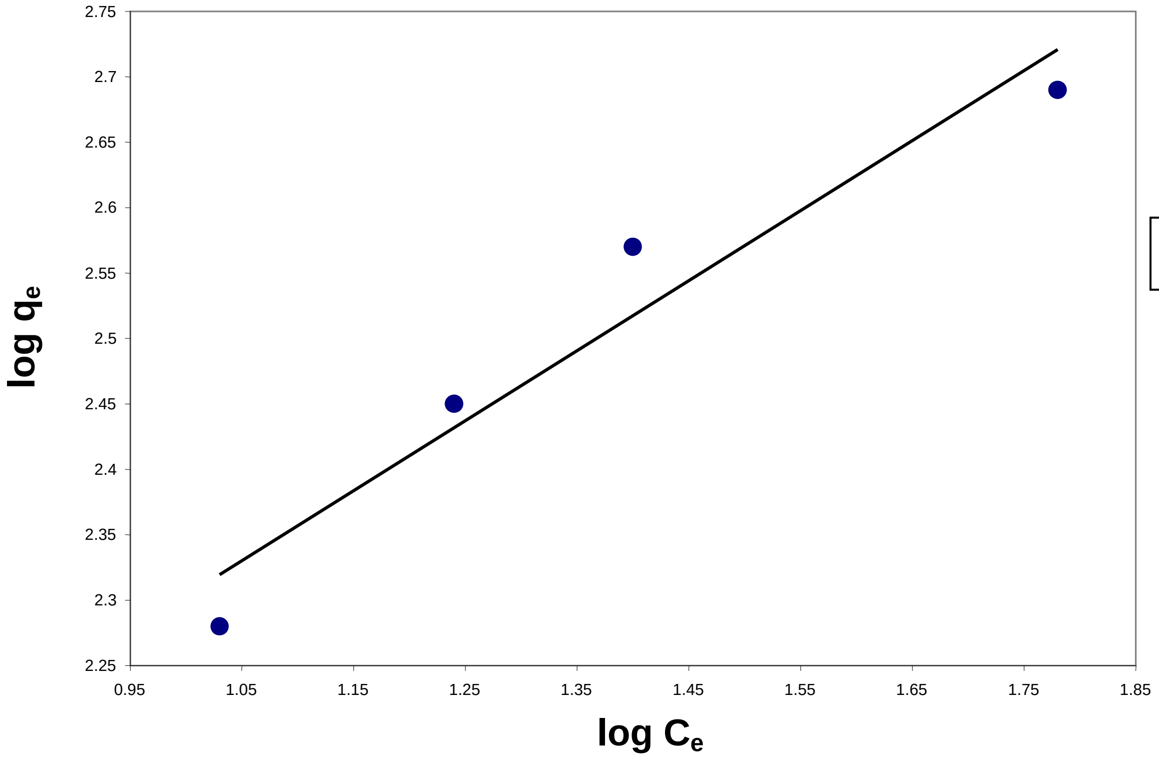

2.75
2.7
2.65
2.6
2.55
2.5
2.45
2.4
2.35
2.3
2.25
0.95
1.05
1.15
1.25
1.35
1.45
1.55
1.65
1.75
1.85
log q_e
log C_e

Fig 6

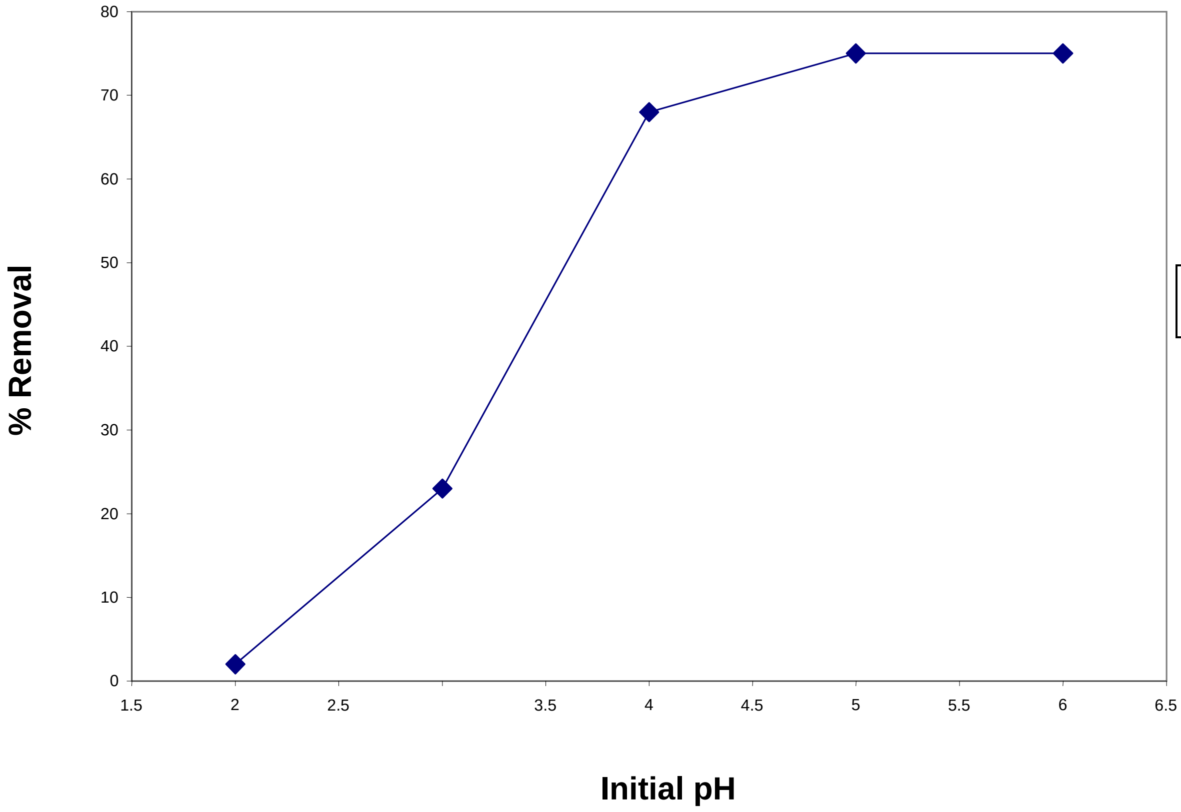


Fig 7

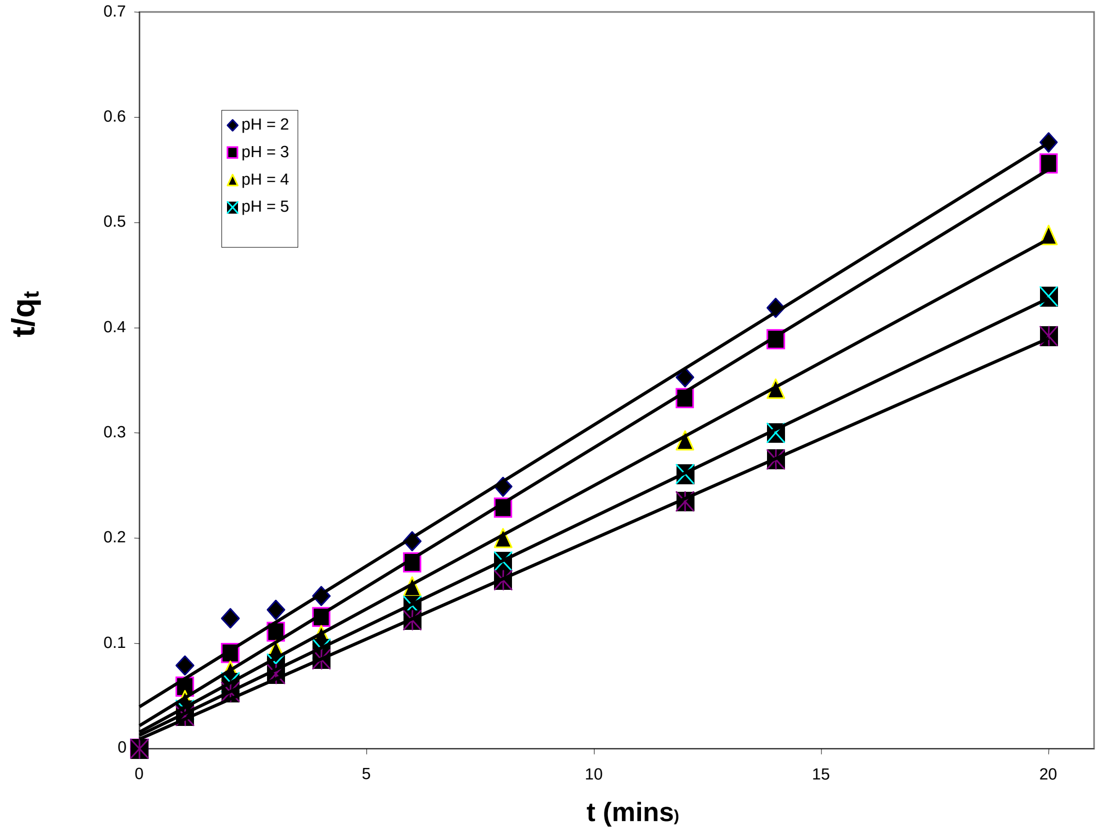


Fig 8

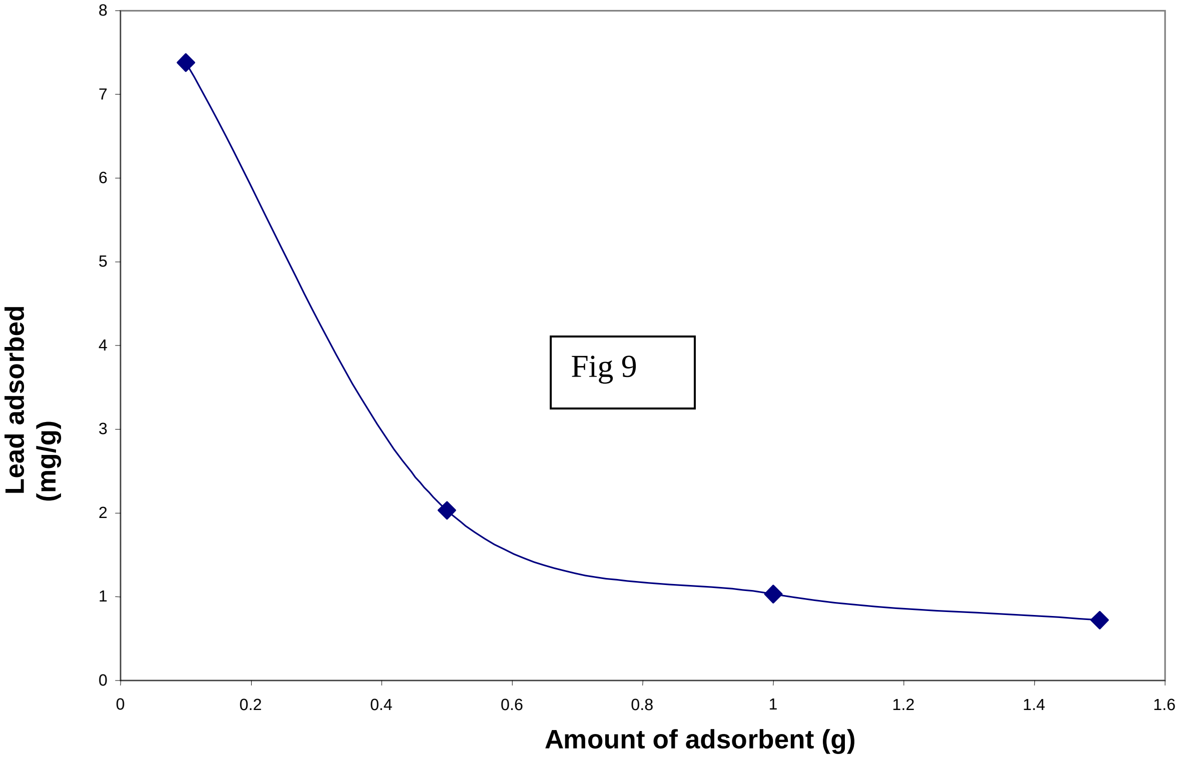


Fig 9
Lead adsorbed (mg/g)
Amount of adsorbent (g)
0
1
2
3
4
5
6
7
8
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

FIGURE LEGENDS

Fig. 1. FTIR spectra of (a) untreated oil palm fibre, (b) treated oil palm fibre and (c) treated oil palm fibre after adsorption.

Fig. 2. The variation of adsorption capacity with adsorption time at various initial lead concentration at 25^0C (pH 7, W = 0.2 g).

Fig. 3. Pseudo-first order kinetics for adsorption of lead by activated carbon produced from treated oil palm fibre at 25^0C.

Fig. 4. Pseudo-second order kinetics for adsorption of lead by activated carbon produced from treated oil palm fibre at 25^0C.

Fig.5. Langmuir adsorption isotherm of lead on activated carbon produced from treated oil palm fibre at 25^0C.

Fig. 6. Freundlich adsorption isotherm of lead on activated carbon produced from treated oil palm fibre at 25^0C.

Fig. 7. Effect of the initial solution pH on the removal of lead by treated oil palm fibre adsorbent (temperature 25^0C; adsorbent concentration 5 g/L; initial dye concentration 100 mg/L).

Fig. 8. Pseudo-second order kinetics for adsorption of lead adsorption by activated carbon produced from treated oil palm fibre at 25^0C.

Fig. 9. Effect of lead adsorbed on adsorbent dose at 25^0C.

TABLE LEGENDS

Table 1. Comparison of the pseudo first- and second-order adsorption rate constants and calculated and experimental q_e values for different initial lead concentrations at 25^{o}C.

Table 2: - Langmuir and Freundlich isotherm constants for lead adsorption at 25^{o}C.

Table 3: Pseudo-second-order rate parameters for sorption of lead on treated oil palm fibre at various initial solution pH values at 25^{o}C.

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