# Isotherm, Kinetic, and Thermodynamic Studies of Lead (II) Biosorption by *Streblus asper*.

**Matthew A. Adebayo, Ph.D.**[1*]; **Adedoyin A. Adebayo, M.Sc.**[2]; **Johnson F. Adediji, Ph.D.**[3]; **and Oluwayemisi T. Adebayo, B.Sc.**[1]

[1]Department of Chemical Sciences, Ajayi Crowther University, Oyo, Oyo State, Nigeria.
[2]Department of Chemistry, Catholic University of Rio de Janeiro – PUC-Rio, Rio de Janeiro, Brazil.
[3]Department of Chemistry, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria.

E-mail: adebayomao@gmail.com*

## ABSTRACT

Biosorption of lead(II) from aqueous solution using *Streblus asper* leaves was investigated via a batch system. The optimum conditions of biosorption were determined by investigating the initial lead (II) concentration, contact time, temperature, biosorbent dose, and pH. The data were analyzed using pseudo second-order, intra-particle diffusion and Elovich models. Information from thermodynamic parameters showed that the biosorption process was spontaneous, endothermic and the randomness at the solid-solution interphase increased during the process. Equilibrium data fitted well into Langmuir, Tempkin, and Dubinin–Radushkevich isotherms. It is evident that *Streblus asper* can be utilized as a good biosorbent for lead(II) removal from aqueous solution.

(Keywords: lead (II), Pb, biosorption, *Streblus asper*, sand paper tree, kinetics, isotherms, thermodynamic)

## INTRODUCTION

Heavy metals are known as hazardous substances because they are toxic even at very low concentrations (Liu, 2008). They are known to be unfriendly to the environment and human health because of their high toxicity, accumulation, and retention in the human body. Lead (II) is one of the known non-biodegradable heavy metals, which accumulates in the aquatic biosphere through myriads of ways (Jalali et al., 2002; Conrad and Hansen, 2007). Severe damage to the kidney, nervous system, reproductive system, liver, and brain has been attributed to lead poisoning in humans (Noeline et al., 2005; Mouflih et al., 2006).

It has been investigated that the concentration of heavy metals in biological tissues is a true reflection of their environmental concentration over a long period of time (Chojnacka, 2009). Removal of heavy metals from water and wastewater is important to protect public health and the environment. Many traditional methods have been applied for the removal of these metals from wastewaters. These include chemical precipitation, ion-exchange, membrane separation, reverse osmosis, evaporation, and electrolysis (Zouboulish et al., 2004; Tewari et al., 2005). These traditional methods are often expensive or are not sufficiently effective in the lowering of concentration ranges (Schiewer and Patil, 2008). Apart from these techniques, adsorption and biosorption also exist.

Biosorption is an emergent, fast growing, and attractive method which involves sorption of heavy metals by a biomass. Biosorption as an alternative means of toxic metals removal requires a combination of active and passive transport mechanisms. The first phase, passive uptake, is an initial rapid and reversible accumulation step while second phase, active uptake, is slower intracellular bioaccumulation, often irreversible and related to metabolic activity (Schiewer and Patil, 2008). This method has many merits ranging from the reusability of biomass, cost effectiveness, improved selectivity for specific metals of interest, removal of heavy metals from solution, and short operation periods (Munagapati et al., 2010).

Sand Paper Tree (*Streblus asper*) is a rigid and densely branched tree. The leaves are very rough (coarse texture) on both sides of the surfaces with finely toothed margin. True to its name, the leaves of sand paper tree are utilized for cleaning cooking utensils and as a substitute for sandpaper. Some people nicknamed the plant as a toothbrush tree. The objective of this study was to investigate the possible potential of the *Streblus asper* leaves for lead (II) removal. The texture and other physical characteristics of *Streblus asper* are expected to enhance its use as biosorbent of lead (II) from aqueous solution. *Streblus asper* leaves were chosen for this work because the plant is widely grown in Africa and the leaves are available at a very low cost.

## MATERIALS AND METHODS

### Preparation of Biosorbent

The leaves of the sand paper plant, *Streblus asper,* used for this research work were collected from the botanical garden located within the University of Ibadan, Ibadan, Nigeria. These leaves were washed with ordinary water and then with de-ionized water to remove dirt. They were later oven-dried at 80°C for 12 h. The dried samples were pulverized in a mortar and pestle and thereafter sieved using a 400-mesh copper sieve. The prepared biosorbent was then preserved in air-tight polyethylene bags.

### Preparation of Lead Solution

All the reagents used in this study were of analytical grade and were used without further purification. The stock solution containing 1000 $mg{\cdot}L^{-1}$ of lead was prepared by dissolving 1.598 g of $Pb(NO_3)_2$ in a 1 L deionized water and making up to the mark with deionized water. The stock solution was used to prepare dilute solutions of different working concentrations.

### Analysis of Lead (II)

The concentration of un-adsorbed lead (II) in the biosorption medium was determined using Atomic Absorption Spectrophotometer (Perkin Elmer model 3100 fitted with a hollow cathode lamp and air-acetylene flame). The instrument response was periodically checked by using standard metal solutions.

### Biosorption Experiments

The biosorption of lead (II) ions on the dried *Streblus asper* biomass was studied in batch experiments. The influences of pH, biosorbent dose, contact time, initial lead (II) ion concentration and temperature on the biosorption capacity were investigated. Each experiment was carried out in duplicate. At the end of each experiment the agitated solution mixture was filtered using Whatmann No.1 filter paper. A 10 mL of the filtrate was quantified for residual lead (II) concentration by Atomic Absorption Spectroscopy.

In order to investigate the effect of pH on biosorption capacity of the biomass, a 400 mg of the biomass was added to 20 mL of 100 $mg{\cdot}L^{-1}$ solutions of each of lead (II) solution at 25°C in 100 mL centrifuge bottles. The experiments were carried out between pH 3 and 9. The accuracy of pH measurements was ± 0.1. The reaction mixtures were then agitated for 10 min on a thermostated water bath shaker at 200 rpm.

The effect of contact time was studied at pH 6.0. Batch biosorption studies were performed by adding a 20 mL of 100 $mg{\cdot}L^{-1}$ of lead (II) solution and a 400 mg of the biomass in a 100 mL centrifuge bottle. Contact time intervals chosen for the analysis varied from 5 min to 180 min at 25ºC.

The influence of initial lead (II) concentration was also studied at pH 6.0. A 400 mg of *Streblus asper* was mixed with a 20 mL of each of lead (II) solution at 10 min of equilibration time.

The variation of temperature on the biosorption capacity of the biosorbent was carried out between 20 and 50ºC at pH 6.0. Mass of biomass was 400 mg while the lead (II) concentration was 100 $mg{\cdot}L^{-1}$ at agitation time of 10 min.

In order to determine the effect of biosorbent dose, varying amounts of *Streblus asper* were added to a 20 mL of 100 $mg{\cdot}L^{-1}$ lead (II) at 25ºC (pH 6.0). The mixtures were then agitated for 10 min on a thermostated water bath shaker at 200 rpm.

The amount of adsorbed lead (II) ($mg{\cdot}g^{-1}$ dry biosorbent) for all experiments carried out was calculated using Equation 1.

$$q_e = \frac{V}{S}.(C_o - C_e) \quad \textbf{(1)}$$

$q_e$ is the amount of lead (II) adsorbed onto the biomass (mg·g$^{-1}$); $C_o$ is the initial lead (II) concentration (mg·L$^{-1}$) while $C_e$ is the equilibrium concentration of the lead (II) solution (mg·L$^{-1}$) after biosorption; $V$ is the volume (L) of the aqueous phase; m is the dry weight (g) of the biomass used.

## RESULTS AND DISCUSSION

### Sorption Studies

**Effect of time on biosorption of lead (II) by *Streblus asper:*** Time dependent study was carried out because biosorption rate is one of the influential factors that must be taken into consideration before planning batch biosorption experiments. The profile of time dependent study of biosorption of lead (II) by *Streblus asper* is presented in Figure 1.

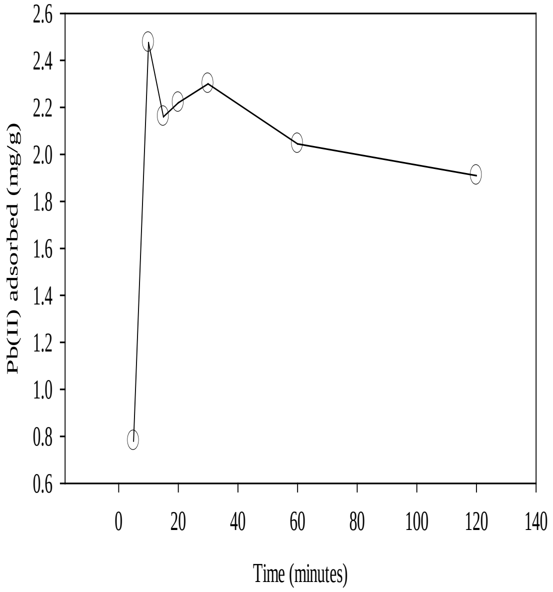

**Figure 1**: Effect of Time on Biosorption of Lead (II) by *Streblus asper* (pH 6; initial lead (II) concentration, 100 mg·L$^{-1}$; Streblus asper dose, 400 mg; temperature, 25°C).

Lead (II) saturation is reached at contact time of 10 min, therefore, the contact time in all our batch experiments was set at 10 min. It can be inferred that the capability of *Streblus asper* to remove lead (II) increased speedily at the initial stage. This fast kinetic process at the initial stage can be attributed to the abundant availability of active binding sites on the biosorbent, which are later occupied as time increases, thereby result in inefficiency of biomass to remove heavy metals at later stage of the biosorption process (Costa and Leite, 1991; Vimala and Das, 2009).

**Effect of temperature on biosorption of lead (II) by *Streblus asper:*** Figure 2 shows the effect of temperature on biosorption of lead (II) by *Streblus asper*. Uptake of lead (II) metal by *Streblus asper* was observed to increase with increase in temperature from 20°C to 50°C. The biosorption process increases with increased temperature, indicating an endothermic process. The relationship between lead (II) uptake by *Streblus asper* and temperature indicates chemical adsorption process.

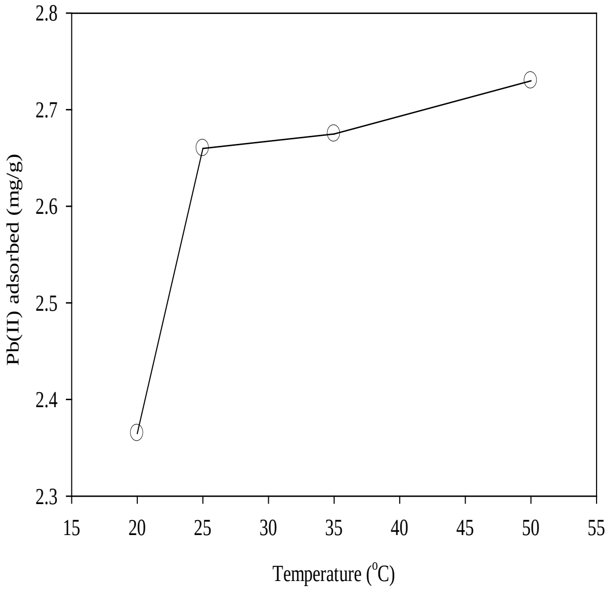

**Figure 2**: Effect of Temperature on Biosorption of Lead (II) by *Streblus asper* (pH 6; initial lead (II) concentration, 100 mg·L$^{-1}$; Streblus asper dose, 400 mg; contact time, 10 min).

**Effect of pH on the lead (II) biosorption by *Streblus asper:*** Biosorption of lead (II) by *Streblus asper* is pH dependent (Figure 3). The equilibrium sorption efficiency has a minimum value (35.3%) at pH 3. Above pH 3, effect of pH became apparent and an increase in metal uptake was observed for lead (II) uptake. The maximum efficiency was achieved at pH 8

(71.9%). It can be inferred from this study that high pH favors lead (II) biosorption by *Streblus asper*.

Sorption of heavy metals from aqueous solutions is a function of properties of adsorbent and molecules of adsorbate transfer from the solution to the solid phase. Abilities of biomass to remove heavy metals are strongly pH sensitive and that adsorption increases as pH of solution increases (Yin et al., 1999). At lower pH, the overall surface charge on biomass is less negative compared to surface charge on biomass at higher pH, which reduces the attraction of positively charged metal cations towards it (Tiemann et al., 2002).

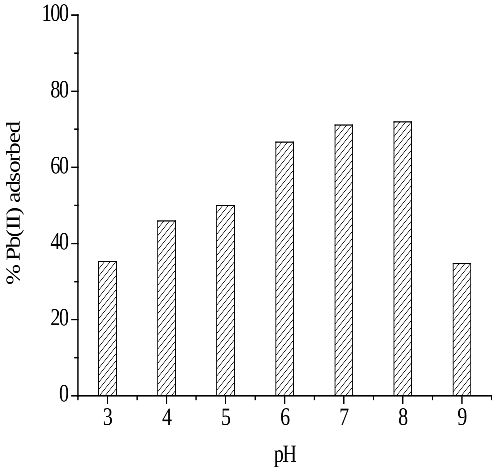

**Figure 3**: Effect of pH on Biosorption of Lead (II) by *Streblus asper* (temperature 25ºC; initial lead (II) concentration, 100 mg·L$^{-1}$; Streblus asper dose, 400 mg; contact time, 10 min).

**Effect of Initial Lead (II) Concentration:** The efficiency of *Streblus asper* to remove lead (II) from aqueous solution at different initial lead (II) concentrations was determined. Figure 4 presents the relation between biosorption efficiency and the metal ion concentrations. It can be inferred from this figure that the metal uptake is directly proportional to metal ion concentration in solution. In general, the data revealed that sorption capacity increased with increase in initial metal ion concentration for the lead (II) on the biomass.

This sorption characteristic indicated that surface saturation is a function of the initial metal ion concentrations. For lower initial metal ion concentrations, the ratio of surface active sites to total amount of metal ions is high; all metal ions can easily interact with the biosorbent and be removed from the solution (Reddy et al., 2010). At low concentrations, therefore, adsorption sites took up the available metal ions quickly. However, at higher concentrations, metal ions have to diffuse to the biomass surface by intraparticle diffusion and greatly hydrolyzed ions will diffuse at a slower rate.

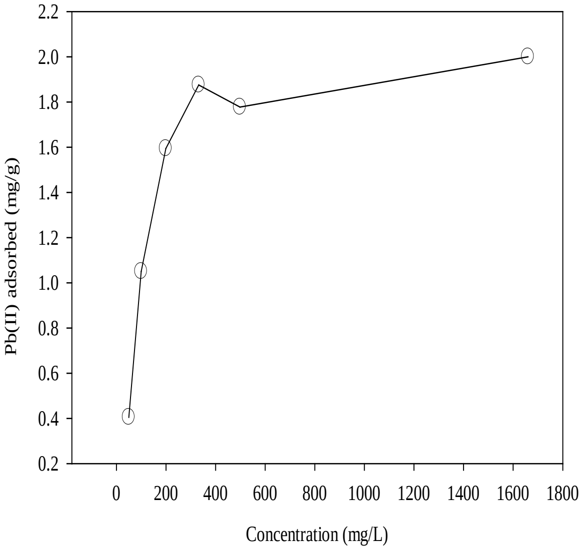

**Figure 4**: Effect of Initial Lead (II) Concentration (pH 6; temperature 25ºC; Streblus asper dose, 400 mg; contact time, 10 min).

**Effect of *Streblus asper* Dosage:** Biosorbent dose has a great influence in biosorption process. Dose of biomass added into the solution determines the number of binding sites available for adsorption (Zafar et al., 2007). Figure 5 shows the effect of biosorbent dose on apparent biosorption capacity of lead (II) by *Streblus asper*. An increase in biomass quantities strongly affects the quantities of metal removed from aqueous solutions. It is evident from Figure 5 that for an initial metal concentration (100 mg·L$^{-1}$), increasing the biomass dose provided greater surface area and availability of more active sites (Ho et al., 1995). The availability of more sites, therefore, led to the enhancement of lead (II) uptake.

Maximum removal of lead (II) was observed with an adsorbent dose of 400 mg. At concentration higher than this value, metal uptake decreased considerably. This phenomenon could be attributed to interference between binding sites at higher concentrations (De Rome and Gadd, 1987).

Reduction in adsorption capacity as biomass concentration increases has also been attributed to an insufficiency of metal ions in solution with respect to available binding sites (Fourest and Roux, 1992). Therefore, for the purpose of this present study, biomass dose of 400 mg was chosen for all the experiments.

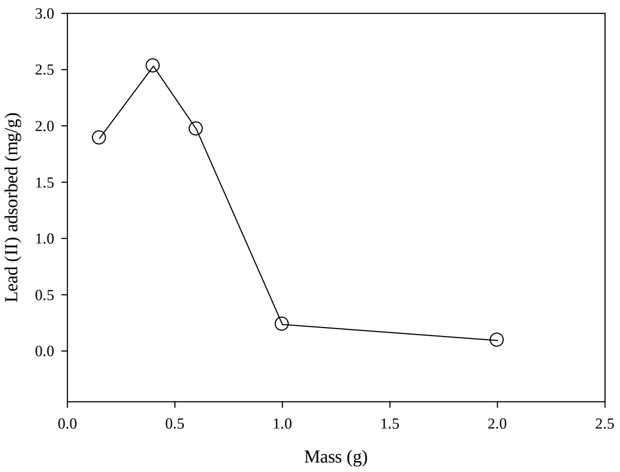

**Figure 5**: Effect of *Streblus asper* Dosage (pH 6; initial lead (II) concentration, 100 mg·L$^{-1}$; temperature, 25ºC; contact time, 10 min).

**Table 1:** Kinetic Parameters for Biosorption of Lead (II) by *Streblus asper.*

| Model | Constants/parameters |
|---|---|
| **Pseudo Second Order** | |
| $k_2$ (g·mg$^{-1}$·min$^{-1}$) | 0.71 |
| $q_e$ (calc.) in mg·g$^{-1}$ | 1.94 |
| $q_e$ (expt.) in mg·g$^{-1}$ | 2.48 |
| $R^2$ | 0.990 |
| **Intraparticle Diffusion Model** | |
| $k_i$ (mg·g$^{-1}$·min$^{1/2}$) | 0.09 |
| $C$ | 1.83 |
| $R^2$ | 0.996 |
| **Elovich Equation** | |
| $\alpha$ (mg·g$^{-1}$·min$^{-1}$) | 4.96 |
| $\beta$ (g·min$^{-1}$) | 4.39 |
| $R^2$ | 0.999 |

**Table 2**: Thermodynamic Parameters for Biosorption of Lead (II) by *Streblus asper.*

| **R$^2$** | $\Delta$***H°*** (kJ·mol$^{-1}$) | $\Delta$***S°*** (kJ·K$^{-1}$·mol$^{-1}$) | $\Delta$***G°*** (kJ·mol$^{-1}$) | | | |
|---|---|---|---|---|---|---|
| | | | $T_1$=293 K | $T_2$=298 K | $T_3$=308 K | $T_4$=323 K |
| 0.925 | 3357.93 | 17.08 | -914.16 | -1717.32 | -1818.40 | -2138.91 |

**Kinetic Study of lead (II) biosorption by *Streblus asper:*** In the quest to investigate the mechanism of biosorption of lead (II) by *Streblus asper* and the potential rate-controlling steps, mass transport and chemical reactions, kinetic models were applied to test our experimental data. Intra-particle diffusion model, Lagergren pseudo first-order, pseudo second-order and Elovich models were employed to test our experimental data. Equation 2 represents Lagergren pseudo first-order model (Lagergren, 1898).

$$Ln(q_e - q_t) = \ln q_e - k_1 t \qquad \textbf{(2)}$$

It was observed that this model could not fit our experimental data because $R^2 << 1$ (data not shown). In Equation 2, $k_1$ ($min^{-1}$) is the pseudo first-order rate constant of biosorption.

The pseudo second-order model is based on the assumption that biosorption follows a second-order mechanism. So, the rate of occupation of adsorption sites is proportional to the square of the number of unoccupied sites (Zafar et al., 2007). Equation (3) shows the linearized form of pseudo second-order equation.

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \qquad \textbf{(3)}$$

$k_2$ is the pseudo second-order rate constant of biosorption; $q_e$ (mg·g$^{-1}$) is the metal uptake at equilibrium; and $q_t$ (mg·g$^{-1}$) is the metal uptake at time, t (min). A plot of ($t/q_t$) against $t$ gives $1/q_e$ as slope. $k_2$ is obtained from the intercept ($1/k_2 q_e^2$). The best fit (see Figure 6), was found to be the pseudo second-order model indicating that the rate-limiting step is a chemical adsorption process between the metals and the *Streblus asper.*

The second-order rate constant for the biosorption of lead (II) from solutions by *Streblus asper* was evaluated to be 0.71 g·mg$^{-1}$·min$^{-1}$ (Table 1). The experimental and calculated values of biosorption capacity ($q_e$) of 2.48 mg·g$^{-1}$ and 1.94 mg·g$^{-1}$, respectively, were in good agreement. The closeness of these values is an indication that the biosorption process is better described by pseudo second-order kinetic model.

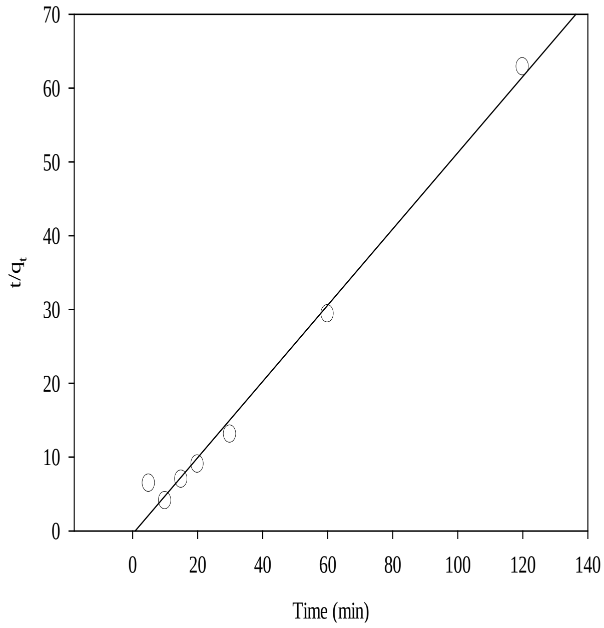

**Figure 6**: The Pseudo Second-Order Plot of the Biosorption of Lead (II) by *Streblus asper* (pH 6; Initial Lead (II) Concentration, 100 mg·L$^{-1}$; temperature, 25ºC)

The relationship between the metal uptake and time is described by intraparticle diffusion model (Weber Jr. and Morriss, 1963) as shown in Equation (4), where $k_i$ is the intraparticle diffusion rate constant.

$$q_t = k_i t^{1/2} + C \qquad \textbf{(4)}$$

The value of $k_i$ (0.09 mg·g $^{-1}$.min$^{1/2}$) was obtained from the slope of the linear plots of $q_t$ versus $t^{1/2}$. As a matter of fact, the intra-particle diffusion is not only rate determining step because a plot of qt versus $t^{1/2}$ has a substantial intercept. The value of intercept *C* was obtained as 1.83. *C* gives information about the boundary layer thickness. The value is low, which means that the boundary effect is small.

The simplified form of Elovich model is given by Equation (5). This equation was based on the principle, which assumed that the adsorption sites increase exponentially with adsorption (Elovich and Larinov, 1962).

$$q_t = \frac{1}{\beta}\ln(\alpha\beta) + \frac{1}{\beta}\ln t \tag{5}$$

In Equation (5), α and β are known as Elovich coefficients α represents the initial sorption rate constant (mg·g$^{-1}$·min$^{-1}$) while β is related to the extent of surface coverage and activation energy for chemisorption (g·mg$^{-1}$). These coefficients were calculated from the plots of $q_t$ versus ln *t*. High correlation coefficient obtained from this plot indicates that Elovich model can be employed to describe the kinetics of biosorption. All the kinetic parameters/constants are presented in Table 1.

## Thermodynamic Studies

The thermodynamic parameters such as standard free energy change ($\Delta G°$), standard enthalpy change ($\Delta H°$) and standard entropy change ($\Delta S°$) were determined by using Equations (6) – (8).

$$\Delta G° = -RT \ln K_C \tag{6}$$

$$K_C = \frac{C_a}{C_e} \tag{7}$$

$$LnK_C = \frac{\Delta S°}{R} - \frac{\Delta H°}{R} \cdot \frac{1}{T} \tag{8}$$

In these equations, *T* represents temperature in Kelvin (*K*); *R* is ideal gas constant (8.314 J·mol$^{-1}$·K$^{-1}$); $K_c$ represents thermodynamic equilibrium constant; $C_a$ represents biomass adsorbed (mg·L$^{-1}$); $C_e$ is the equilibrium concentration of solution in (mg·L$^{-1}$). Equation (8) is a known as van't Hoff equation. The values of $\Delta H°$ and $\Delta S°$ (Table 2) for the biosorption of each of the metal ions on *Streblus asper* were calculated from the slope of the plot of ln K versus $T^{-1}$ as shown in Figure 7.

The negative values of $\Delta G°$ (Table 2), which increases as temperatures increases, confirm the feasibility and spontaneous nature of the biosorption process (Aksu and Tunc, 2005). It was also noted that the change in free energy increased with increase in temperature (from 288 – 323 K) for the biosorption of lead (II), which exhibited an increase in biosorption with rise in temperature. The positive values of $\Delta H°$ and $\Delta S°$ for the biosorption are indications that the process is endothermic and shows increased randomness at solid-solution interface during the biosorption of the metal ions on *Streblus asper* (Sarin et al., 2006; Yurtsever and Şengil, 2009).

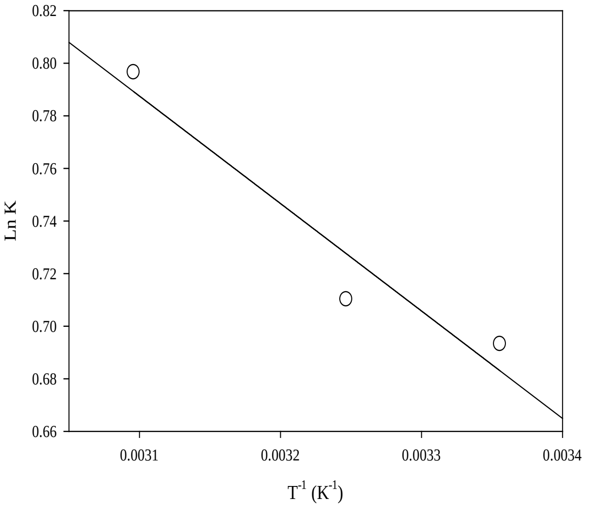

**Figure 7**: Thermodynamic Plot of the Biosorption of Lead (II) by *Streblus asper* (pH 6; biomass dose, 400 mg; agitation time, 10 minutes: concentration100 mg·L$^{-1}$).

## Application of Adsorption Isotherm Models

Equilibrium data modeling has a myriad of industrial applications in the field of adsorption. It gives information for comparison among different biomaterials under different operational conditions, designing and optimizing operating procedures (Benguella and Benaissa, 2002). The biomass (*Streblus asper*) exhibited adsorption isotherms of Langmuir, Tempkin and Dubinin–Radushkevich.

To examine the relationship between metal uptake ($q_e$) and aqueous concentrations ($C_e$) at equilibrium, sorption isotherm models are widely employed for fitting experimental data, of which the Langmuir equation is the most widely used. The Langmuir model (Langmuir, 1918) has been used empirically because it contains the two useful parameters ($q_m$ and *b*), which are understandable since they reflect the two important characteristics of the sorption system (Holan and Volesky,1994; Volesky and Holan, 1995). It provides information on uptake capabilities and is capable of reflecting the usual equilibrium sorption process behavior.

Langmuir assumed that the forces that are exerted by chemically unsaturated surface atoms (total number of binding sites) do not extend further than the diameter of one sorbed molecule and therefore sorption is restricted to a monolayer. If the metal ions are taken up independently on a single type of binding site in such a way that the uptake of the first metal ion does not affect the sorption of the next ion, then the sorption process would follow the Langmuir adsorption equation (Equation 9).

$$\frac{1}{q_e} = \frac{1}{q_\mathrm{m}} + \frac{b}{q_m}.\frac{1}{C_e} \tag{9}$$

The parameters $q_m$ and $b$ in the linearized Langmuir isotherm represent the maximum metal adsorption and affinity parameter, respectively. A low value of $b$ means lower affinity of the biosorbent for the biomass. The maximum lead (II) biosorption by *Streblus asper* is 3.06 mg·g$^{-1}$ while the affinity parameter is 50.08.

Another useful model, which is based on the assumption that the free energy of adsorption is dependent on the surface coverage and takes into account the interactions between adsorbents and metal ions is known as the Tempkin isotherm (Tempkin and Pyzhev, 1940). Equation 10 represents the mathematical statement of Tempkin isotherm.

$$q_e = B \ln A + B \ln C_e \tag{10}$$

where $B = \dfrac{RT}{b}$

A plot of $q_e$ versus ln $C_e$ enables the determination of the Tempkin constants, $A$ and $B$. $A$ is the equilibrium binding constant corresponding to the maximum binding energy (L·mg$^{-1}$); $B$ is related to the heat of adsorption; $b$ is the Temkin isotherm constant; T (K) is the absolute temperature and R is the ideal gas constant (8.314 J·mol$^{-1}$·K$^{-1}$).

An isotherm that distinguishes between the physical and chemical biosorption, the Dubinin–Radushkevich (D-R) isotherm model (Dubinin and Radushkevich, 1947), was also used in analysis of our data. Equation (11) shows the D-R isotherm.

$$\ln q_e = \ln q_m - \beta \varepsilon^2 \tag{11}$$

Where $\beta$ is a constant that is related to the mean free energy of biosorption per mole of the biosorbate (mol$^2$·kJ$^{-2}$); $q_m$ is the theoretical saturation capacity (mol·g$^{-1}$); and $\varepsilon$ is known as the Polanyi potential (Equation 12).

$$\varepsilon = \mathrm{RT} \ln \left(1 + \frac{1}{C_e}\right) \tag{12}$$

where R (J·mol$^{-1}$·K$^{-1}$) is the ideal gas constant, and T (K) is the absolute temperature. A plot of *ln* $q_e$ against $\varepsilon^2$, enabled the determination of the value of $q_m$ (mol·g$^{-1}$) from the intercept and the value of $\beta$ from the slope. The constant $\beta$ gives is related to the free energy, $E$ (kJ·mol$^{-1}$), of biosorption per mole of the biosorbate. The value of $E$ can be evaluated using the relationship in Equation (13) (Dubey and Gupta 2005).

$$E = \frac{1}{(2\beta)^{\frac{1}{2}}} \tag{13}$$

The value of $E$ gives information about the type of biosorption mechanism: either chemical ion-exchange or physical biosorption. The free energy of transferring a mole of solute from solution to surface of *Streblus asper* was calculated to be 5.00 kJ·mol$^{-1}$ (Table 3) indicating that the biosorption may occur via a chemical ion-exchange mechanism.

**Table 3**: Langmuir, Tempkin, and Dubinin–Radushkevich Constants for Biosorption of Lead (II) by *Streblus asper.*

| **Model** | **Values** |
|---|---|
| **Langmuir** | |
| $b$ (L·g$^{-1}$) | 50.08 |
| $q_{max}$ (mg·g$^{-1}$) | 3.06 |
| $R^2$ | 0.925 |
| **Tempkin** | |
| $A$ (L·mg$^{-1}$) | 1.66 |
| $B$ | 1.71 |
| $B$ | 1448.11 |
| $R^2$ | 0.971 |
| **Dubinin–Radushkevich** | |
| $q_m$ (mg·g$^{-1}$) | 7.59 |
| $\beta$ (mol$^2$·kJ$^{-2}$) | 2 x 10$^{-8}$ |
| $E$ (kJ·mol$^{-1}$) | 5.00 |
| $R^2$ | 0.987 |

Table 3 reports the all parameters obtained from Langmuir, Tempkin and Dubinin–Radushkevich isotherm models.

## CONCLUSION

The present study explored the biosorption of lead (II) from aqueous solution using biomass prepared from *Streblus asper* leaves via a batch system. The optimum conditions of biosorption were determined by investigating the initial metal ion concentration, contact time, temperature, biosorbent dose and pH. Lead (II) uptake is a function of temperature and high pH favored the biosorption process. The biosorption process was a fast kinetic process. The data were analyzed using pseudo second-order, intra-particle diffusion and Elovich models. Information from $\Delta G^o$, $\Delta H^o$, and $\Delta S^o$ showed that the biosorption process was spontaneous, endothermic and the randomness at the solid-solution interphase increased during the biosorption process. Equilibrium data fitted well into Langmuir, Tempkin, and Dubinin–Radushkevich isotherms. This study revealed that the low cost *Streblus asper* can be widely used for removal of lead (II) from aqueous solution and probably for waste-water treatment.

## REFERENCES

1. Aksu, Z. and O. Tunc. 2005. “Application of Biosorption for Penicillin G Removal: Comparison with Activated Carbon”. *Process Biochemistry*. 40:831-847.

2. Benguella, B. and H. Benaissa. 2002. “Cadmium Removal from Aqueous Solution by Chitin: Kinetic and Equilibrium Studies”. *Water Research.* 36:2463-2474.

3. Chojnacka, K. 2009. *Biosorption and Bioaccumulation in Practice*. Nova Science Publishers: New York, NY.

4. Conrad, K. and H.C.B. Hansen. 2007. “Sorption of Zinc and Lead on Coir”. *Bioresource Technology*. 98:89-97.

5. Costa, A.C.A. and S.G.C. Leite. 1991. “Metal Biosorption by Sodium Alginate Immobilized *Chlorella homosphaera*”. *Biotechnology Letters*. 13:559-562.

6. De Rome, L. and G.M. Gadd. 1987. “Copper Adsorption by *Rhizopus arrhizus*, *Cladosporium resinae* and *Penicillium italicum”*. *Applied Microbiology and Biotechnology*. 26:84-90.

7. Dubey, S.S. and R.K. Gupta. 2005. “Removal Behaviour of Babool bark (*Acacia nilotica*) for *Submicro concentrations* of Hg2+ from Aqueous Solutions: A Radiotracer Study”. *Separation and Purification Technology*. 41:21-28.

8. Dubinin, M.M. and L.V. Radushkevich. 1947. “Equation of the Characteristic Curve of Activated Charcoal”. *The Proceedings of Academy of Science. USSR Physical Chemistry Section.* 55:331-333.

9. Elovich, S.Y. and O.G. Larinov. 1962. “Theory of Adsorption from Solutions of Non-Electrolytes on Solid (I) Equation of Adsorption from Solutions and the Analysis of its Simplest Form, (II) Verification of the Equation of Adsorption Isotherm from Solutions”. *Izv. Akad. Nauk. SSSR, Otd. Khim. Nauk.* 2:209-216.

10. Fourest, E. and J.C. Roux. 1992. “Heavy Metal Biosorption by Fungal Mycelia by-product: Mechanism and Influence of pH”. *Applied Microbiology and Biotechnology*. 37:399-403.

11. Ho, Y.S., D.A.J. Wase, and C.F. Forster. 1995. “Batch Nickel Removal from Aqueous Solution by Sphagnum Moss Peat”. *Water Resources*. 29:1327-1332.

12. Holan, Z.R. and B. Volesky.1994. “Biosorption of Pb and Ni by Biomass of Marine Algae”. *Biotechnology and Bioengineering*. 43:1001-1009.

13. Jalali, R., H. Ghafourian, Y. Asef, S.J. Davarpanah and S. Sepehr. 2002. “Removal and Recovery of Lead using Non-Living Biomass of Marine Algae”. *Journal of Hazardous Materials*. 92:253-262.

14. Lagergren, S. 1898. “About the Theory of So-Called Adsorption of Soluble Substances”. *K., Sven. Ventenskapsakad. Handl.* 24:1-39.

15. Langmuir, I. 1918. “The Adsorption of Gases on the Plane Surfaces of Glass, Mica, and Platinum. *Journal of the American Chemical Society.* 40:1361-1403.

16. Liu, C., R. Bai, and Q.S. Ly. 2008. “Selective Removal of Copper and Lead Ions by Diethylenetriamine-Functionalized Adsorbent: Behaviours and Mechanisms”. *Water Research*. 42:1511-1522.

17. Mouflih, M., A. Aklil, N. Jahroud, M. Gourai, and S. Sebti. 2006. “Removal of Lead from Aqueous Solutions by Natural Phosphate”. *Hydrometallurgy*. 81:219-225.

18. Munagapati, V.S., V. Yarramuthi, S.K. Nadavala, S.R. Alla, and K. Abburi. 2010. “Biosorption of Cu (II), Cd (II) and Pb (II) by *Acacia leucocephala* bark Powder: Kinetics, Equilibrium and Thermodynamics”. *Chemical Engineering Journal*. 157:357-365.

19. Noeline, B.F., D.M. Manohar, and T.S. Anirudhan. 2005. “Kinetic and Equilibrium Modeling of Lead(II) Sorption from Water and Wastewater by Polymerized Banana Stem in a Batch Reactor”. *Separation and Purification Technology*. 45:131-140.

20. Reddy, D.H.K., K. Seshaiah, A.V.R. Reddy, M.M. Rao, and M.C. Wang. 2010. “Biosorption of $Pb^{2+}$ from Aqueous Solutions by *Moringa oleifera* Bark: Equilibrium and Kinetic Studies”. *Journal of Hazardous Materials*. 174:831-838.

21. Sarin, V., T.S. Singh, and K.K. Pant. 2006. “Thermodynamic and Breakthrough Column Studies for the Selective Sorption of Chromium from Industrial Effluent on Activated Eucalyptus Bark”. *Bioresource Technology*. 97:1986-1993.

22. Schiewer, S. and S.B. Patil. 2008. “Modeling the Effect of pH on Biosorption of Heavy Metals by Citrus Peels”. *Journal of Hazardous Materials*. 157:8-17.

23. Tempkin, M.J. and V. Pyzhev. 1940. “Kinetics of Ammonia Synthesis on Promoted Iron Catalysts”. *Acta Physicochimica. URSS*. 12:217-256.

24. Tewari, N., P. Vasudevan, and B.K. Guha. 2005. “Study on Biosorption of Cr (VI) by *Mucar hiemalis*”. *Biochemical Engineering Journal*. 23:185-192.

25. Tiemann, K.J., G. Gamez, K. Dokken, J.G. Parsons, and J.L. Gardea-Torresdey. 2002. “Chemical Modification and X-ray Absorption Studies for Lead(II) binding by *Medicago sativa* (Alfalfa) Biomass”. *Microchemical Journal*. 71:291-292.

26. Vimala, R. and N. Das. 2009. “Biosorption of Cadmium (II) and Lead (II) from Aqueous Solutions using Mushrooms: A Comparative Study”. *Journal of Hazardous Materials*. 168:376-382.

27. Volesky, B. and Z.R. Holan. 1995. *Biosorption of Heavy Metals*. *Biotechnology Progress*. 11:235-250.

28. Weber, Jr. W.J. and J.C. Morriss. 1963. “Kinetics of Adsorption of Carbon from Solution”. *Journal of Sanitary Engineering Division. Proceedings of American Society of Civil Engineering*. 89:31-60.

29. Yin, P.H., Q.M. Yu, and Z. Ling. 1999. “Biosorption Removal of Cadmium from Aqueous Solution by using Pretreated Fungal Biomass Cultured from Starch Wastewater”. *Water Research.* 33:1960-1963.

30. Yurtsever, M. and I.A. Şengil. 2009. “Biosorption of Pb(II) Ions by Modified *Quebracho tannin* Resin”. *Journal of Hazardous Materials*. 163:58-64.

31. Zafar, M.N., R. Nadeem, and M.A. Hanif. 2007. “Biosorption of Nickel from Protonated Rice Bran”. *Journal of Hazardous Materials*. 143:478-485.

32. Zouboulish, A.I., M. Loukidou, and K.A. Matis. 2004. “Biosorption of Toxic Metals from Aqueous Solutions by Bacteria Strains Isolated from Metal Polluted Soils”. *Process Biochemistry*. 39:909-916.

## ABOUT THE AUTHORS

**Dr. M.A. Adebayo** is a Lecturer I in Ajayi Crowther University, Oyo-Nigeria. He holds a Ph.D. in Physical Chemistry from the University of Ibadan, Ibadan, Nigeria. His research interests are in the area of biophysical chemistry, membrane biochemistry, bioinorganic chemistry, and environmental chemistry.

**A.A. Adebayo,** is a doctoral research fellow in the Department of Chemistry, Catholic University of Rio de Janeiro – PUC-Rio, Rio de Janeiro, Brazil. She holds a Master of Science degree (M.Sc.) in Environmental and Pollution Control from the University of Ibadan, Ibadan, Nigeria. Her research interests are in analytical/inorganic and environmental chemistry.

**J.F. Adediji,** holds a Ph.D. in Chemistry from the University of Ilorin, Ilorin, Nigeria. He is a Lecturer I in the Department of Chemistry, Federal University of Agriculture, Abeokuta-Nigeria. His research interests are in bioinorganic chemistry and environmental chemistry.

**O.T. Adebayo**, a research graduate, holds a Bachelor of Science (B.Sc.) degree in Industrial Chemistry from Ajayi Crowther University, Oyo-Nigeria.

## SUGGESTED CITATION

Adebayo, M.A., A.A. Adebayo, J.F. Adediji, and T.O. Adebayo. 2012. "Isotherm, Kinetic, and Thermodynamic Studies of Lead (II) Biosorption by *Streblus asper*". *Pacific Journal of Science and Technology*. 13(2):283-293.

Pacific Journal of Science and Technology