Kinetic Model for the Sorption of Ni(II), Cu(II) and Zn(II) onto Cocos Mucifera Fibre Waste Biomass from Aqueous Solution

Augustine K. Asiagwu1, Hilary I. Owamah2 and Izinyon O. Christopher3
1Chemistry Department, Delta State University, Abraka, P.M.B.1, Delta State, Nigeria
2Civil Engineering Department, Landmark University, P.M.B1001, Omu-Aran, Kwara State Nigeria
3Civil Engineering Department, University of Benin, Benin, Nigeria

Abstract
Sorption of divalent metals ions Ni(II), Cu(II) and Zn(II) unto coconut cocus mucifera fibre waste biomass over a wide range of operation conditions and equilibrium-sorption kinetics were studied. The batch experiment showed that pH 2-3, was the best range for the sorption of the metal ions onto the biomass. The time-dependent experiments showed that the binding of the metal ions onto the adsorbent, was quite rapid and occurred within 25 minutes and completed within 50 minutes. The sorption process was examined by means of the Langmuir and the Freundlich isotherm models. The monolayer sorption capacity obtained using the Langmuir equation was 0.08 mg/g Ni (II), 0.08 mg/g Cu(II) and 0.09 mg/g Zn(II). The Freundlich isotherm model was not too appropriate for the sorption process, since R2 for all the three metals are less than 0.90. However the Kf value of Zn(II) (0.880), is greater than that of Ni(II) (0.077) and Cu(II) (0.075), suggesting that Zn(II) has greater adsorption tendency towards the biomass. The kinetics of the sorption mechanism was evaluated using the pseudo-first order rate model and pseudo-second rate model. The results indicated that the pseudo-second order model provides a more appropriate description of the single and mixed metal-ion sorption process of Ni(II) (Cu(II)) and Zn(II) onto coconut fibre biomass.

Keywords: Metal ions adsorption process; Adsorption conditions and sorption kinetics

Introduction
The increasing levels of metals in the environment from various anthropogenic sources have become a source of concern for environmentalists and scientists alike. Unlike the toxic organics that in many cases can be degraded, metals deposited into the environment tend to persist indefinitely, accumulating in living tissues through food chain. These effects and many others have made it necessary to adapt measures that will help remove these heavy metals from wastewater, surface and groundwater supplies, using any available cost effective means. The problems of our ecosystem are increasing with advancement in technology. Heavy metal pollution is one of these problems. Toxic heavy metal release into the environment has been increasing continuously as a result of man’s industrial activities and technological development.

The release of these heavy metals poses a significant threat to the environment and public health because of their toxicity, bioaccumulation in food chain and persistence in nature [1]. Lead is a heavy metal that affects the functioning of the blood, liver, kidney and brains of human beings. Lead is a component of most industrial and domestic paints. Nickel which causes gastrointestinal irritation and lung cancer is often obtained from Ni/Fe storage batteries. Due to the magnitude of the problem of heavy metal pollution, research into new and cheap methods of removal has been on the increase recently. Several workers have reported on the potential use of agricultural by-products as good adsorbsents for the removal of metal ions from aqueous solutions and waste water [2].

This process attempts to put into use the principle of using waste to treat waste and becomes even more efficient because these agricultural by-products are readily available and often pose some waste disposal problems. Hence, they are available at little or no cost, since they are waste products. This makes the process of treating waste waters with agricultural by-products adsorbents more cost effective than the use of conventional adsorbents like commercial activated carbon.

In addition, there is no need for a complicated regeneration process when using agricultural by-products for waste water treatment [3]. The ability of some agricultural by-products to adsorb heavy metals from waste water and aqueous solutions has been reported in literatures and these include: Cotton seed hulls, rice straw and sugarcane bagasse, maize cob [3,4]. Physio-chemical methods such as chemical precipitation, lime coagulation, ion exchange, solvent extraction, reverse osmosis, chemical oxidation or reduction, electrochemical treatment, evaporation recovery, filtration and membrane technologies have been widely used to remove heavy metal ions from industrial wastewater [5-8]. These processes may be ineffective or expensive and non-environment friendly, especially when the heavy metal ions in solutions are contained in the order of 1-100 mg of the dissolved heavy metal ions [9].

Moreover, the disadvantage like incomplete metal removal, high reagent and energy requirements, generation of toxic sludge or other waste products that require careful disposal has made it imperative for a cost effective treatment method that is capable of removing heavy metals from aqueous effluents. In recent times, a great deal of interest has been given to the utilization of agricultural by-products as adsorbents for removal of trace amounts of toxic and valuable heavy metals from municipal and industrial wastewater, particularly because of low cost, high availability of these materials, absence of complicated...

*Corresponding author: Hilary I. Owamah, Civil Engineering Department, Landmark University, P.M.B1001, Omu Aran, Kwara State Nigeria, Phone: +2340835705814; E-mail: dahilla222@yahoo.com
Received October 26, 2012; Accepted December 29, 2012; Published December 31, 2012


Copyright: © 2013 Asiagwu AK, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.
regeneration process and their capability of binding to heavy metals by adsorption, chelation and ion-exchange [10,11,13].

This present study is aimed at determining the optimum conditions for the sorption of three divalent metals Ni(II), Cu(II) and Zn(II) onto cocos mucifera fibre, via equilibrium adsorption isotherms and kinetic studies. The equilibrium of the adsorption process is often described by fitting the experimental points with models usually used for the representation of equilibrium adsorption isotherm [12]. The isotherm models for single-solute system are the Langmuir and Freundlich isotherm models. Evaluation of equilibrium sorption performance needs to supplemented by process-oriented studies of the kinetics and eventually by dynamic continuous flow tests.

Presently, we are not yet aware of any proven documented work on the efficient reuse and recycling of cocos mucifera waste. It is on this premise that this study was undertaken to investigate the possibility of using cocos mucifera waste as a cost effective adsorbent for heavy metals removal from wastewater.

Experimental

Sample collection

20 fresh coconuts (cocos mucifera) were collected from a farm in Eku in Ethiope East Local Government Area of Delta State, Nigeria. These were all hand plucked from the trees thoroughly washed and the fibre carefully carved out of the shell. The fibres, while still fresh, were washed with deionized water and allowed to air-dry. The dried fibres were torn into shreds and cut into small chips; these were then sun-dry for five days. The dried samples were ground using mechanical grinder and then severed through a B.S. standard screen to obtain a particle size of 100µm and stored in a plastic container for further analysis.

Activation and purification of the biomass

It is often necessary to activate a solid before using it as an adsorbent for sorption studies. The purpose of activation is to increase the surface area of the solid by introducing a suitable degree of porosity into the solid matrix [13]. Again, activation may also produce structural defects in solids, which may be favorable to sorption processes [14]. The experiments on activation and purification of the biomasses were carried out according to the previous works of [15]. 500 g of finely divided biomass was activated and at the same time, purified by soaking in excess 0.3 M HNO₃ for 24 hours to remove any metals and debris that might be in the biomass prior to experimental metal ion exposure, followed by washing thoroughly with deionized water until a pH of 7.1 ± 0.1 was attained and then air-dried. The air dried biomass was then washed with deionized water and re-suspended in 2M hydroxylamine using a mechanical grinder and then filtered through a B.S. standard screen to obtain a particle size of 200µm and stored in a plastic container for further analysis.

Effect of metal ion concentration on sorption

The experiment on the effect of metal ion concentration on sorption was performed according to the pervious works of [13]. Activated/purified biomasses (2.50 ± 0.01mg) were weighed into several flasks. Ni(II), Cu(II) and Zn(II) solution (2.50mg in 50ml of water) were added to the biomasses. The flasks were then labeled for time intervals of 5,10,15,20,25,30,40 and 50 minutes. The pH's of these suspensions were adjusted to 5.0. The flasks were tightly covered and shaken at the appropriate time intervals. At the end of each interval, the suspensions were filtered using Whiteman No. 45 filter paper and then centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached.

Data evaluation

The Ni(II), Cu(II) and Zn(II) contents in all experiments were determined using Atomic Adsorption Spectrometer (AAS). Spectroscopic grade standards were used to calibrate the instruments, which were checked throughout the analysis for instrument's response. The batch experiments were performed in triplicates and the means were computed for each set of values for quality assurance.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ash Content</td>
<td>5.8</td>
</tr>
<tr>
<td>2</td>
<td>Moisture content</td>
<td>4.6</td>
</tr>
<tr>
<td>3</td>
<td>Total pore volume</td>
<td>0.71</td>
</tr>
<tr>
<td>4</td>
<td>Iodine number</td>
<td>600</td>
</tr>
<tr>
<td>5</td>
<td>Surface Area(m²/g)</td>
<td>630</td>
</tr>
<tr>
<td>6</td>
<td>Volatile matter</td>
<td>1.9</td>
</tr>
<tr>
<td>7</td>
<td>Mean particle size(mm)</td>
<td>0.11</td>
</tr>
<tr>
<td>8</td>
<td>Apparent density(g/ml)</td>
<td>0.60</td>
</tr>
<tr>
<td>9</td>
<td>Fixed carbon</td>
<td>69.5</td>
</tr>
<tr>
<td>10</td>
<td>pH</td>
<td>6.5</td>
</tr>
<tr>
<td>11</td>
<td>Methylene blue number</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>Micropore volume(m³/µl)</td>
<td>0.14 ± 0.02</td>
</tr>
</tbody>
</table>

Table 1: Physical properties of the different types of adsorbents.

to accurately weighed (2.50±0.01mg) activated/purified biomass in different flasks and agitated for 50 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached. The end of the time, the suspensions was filtered through Whatman No. 45 filter paper and centrifuged at 2800 rpm for 5 minutes to ensure that equilibrium was reached.
the actual percent removal of the metal ions from solutions was found to increase with increase in initial metal-ion concentration (Figure 1) this may be due to the fact that at lower concentrations, adsorption of the metal-ions occurred slowly, and further increase in initial metal-ion concentration led to a competition for available bonding sites on the biomass surface by the metal-ions and thus increased adsorption. Similar adsorption patterns have also been reported by other researchers [9,18-22].

Effect of contact time

Time dependence experiments were conducted in order to obtain how long the coconut fiber waste biomass would take to absorb the metal-ions at optimum pH. The data from the time dependent experiments for the removal of the trace metals is as presented in table ( ).

\[ q_e = \frac{V}{M} (C_0 - C_e) \]
\[ q_e = \text{metal-ion concentration on the biomass (mg/g) at equilibrium.} \]
\[ C_e = \text{metal-ion concentration in solution (mg/l) at equilibrium.} \]
\[ C_0 = \text{initial metal-ion concentration in solution (mg/l).} \]
\[ V = \text{volume of solution (L).} \]
\[ M = \text{Mass of biomass used (g).} \]

Kinetic treatment of experimental data

In order to comprehensively investigate the mechanism of adsorption, the pseudo – first order and the pseudo-second order equations as have been used in [16,17] were applied to the experimental data. The linear form of pseudo-first order model is given by Equation (2):

\[ \ln (q_e - q_t) = \ln q_e - Kt \]
\[ q_e = \text{mass of metal adsorbed at equilibrium (mg/g).} \]
\[ q_t = \text{mass of metal adsorbed at time t (mg/g).} \]
\[ K = \text{equilibrium constant.} \]
\[ A \text{ linear plot of ln (} q_e - q_t) \text{ versus } t \text{ confirms the model.} \]

The pseudo – second order equation earlier used for the sorption system of divalent metal-ions using sphagnum moss plant was adopted [16]. The linear form of the pseudo-second order model is generally expressed as given in Equation (3):

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

Results and Discussions

Effect of metal-ion concentration

The experimental results of the uptake of Ni(II), Cu(II) and Zn(II) ions onto the coconut fiber waste biomass at various initial metal ion concentrations are as shown in table 2 and figure 1. The sorption capacity increased from 0.08-0.085 mg/g Ni(II); 0.077-0.079 mg/g Cu(II); and 0.081 -0.091 mg/g Zn(II), with increase in the metal ion concentration from 10-80 mg/l at biomass dose of 2.5 mg. The three metals in this study were adsorbed in this order: Zn(II) > Cu (II)> Ni(II). However,
and rapid, implying that adsorption was taking place on the cell surface process. Again, the adsorption mechanism for these metals were stable mechanism for the metals investigated might be an ion exchange decrease with further increase pH. This indicates that the adsorption three metal-ions were similar; being highest at pH 5 and then began to decrease with further increase pH. This indicates that the adsorption mechanism for the metals investigated might be an ion exchange process. Again, the adsorption mechanism for these metals were stable and rapid, implying that adsorption was taking place on the cell surface of the coco-nut fibre waste biomass. The trend of this pH-dependent adsorption suggests that by reducing the pH, the bound metal-ions could be desorbed, and the spent biomass regenerated. Once the metals are recovered, the biomass material, which is biodegradable, will cause no environmental damage and may be utilized as natural soil conditioners or fertilizers. Hence, the dry coconut fibre waste biomass could be used for cleaning the environment and industrial effluents. Similar findings using other biomaterials have been observed by other researchers [19,13,22].

**Effect of pH**

Biosorbent materials are made up of complex, organic residues such as lignin and cellulose, which contain different types of polar functional groups. These groups can be actively involved in chemical bonding, and may be responsible for the typical cation exchange characteristics evident in biomaterials. The pH dependence data for the sorption of the three metals under investigation are presented in table 4 and figure 3.

The data showed that the sorption of Ni(II), Cu (II) and Zn(II) increased as pH increased from 2-5, with optimum adsorption of 82-86%, occurring between pH 2 and 3. Above pH 5, a gradual decrease in the amount of metal-ions removed by the biomass was observed. In general, this pH-dependent study showed that the sorption of the three metal-ions were similar; being highest at pH 5 and then began to decrease with further increase pH. This indicates that the adsorption mechanism for the metals investigated might be an ion exchange process. Again, the adsorption mechanism for these metals were stable and rapid, implying that adsorption was taking place on the cell surface

<table>
<thead>
<tr>
<th>pH</th>
<th>Amount of metal ion adsorbed (mg/g), q_e</th>
<th>Amount of metal ion adsorbed (mg/g),</th>
<th>Amount of metal ion adsorbed (mg/g), q_e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni(II)</td>
<td>Cu(II)</td>
<td>Zn(II)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.082</td>
<td>0.078</td>
<td>0.085</td>
</tr>
<tr>
<td>3</td>
<td>0.082</td>
<td>0.080</td>
<td>0.085</td>
</tr>
<tr>
<td>4</td>
<td>0.084</td>
<td>0.082</td>
<td>0.086</td>
</tr>
<tr>
<td>5</td>
<td>0.084</td>
<td>0.083</td>
<td>0.083</td>
</tr>
<tr>
<td>6</td>
<td>0.079</td>
<td>0.076</td>
<td>0.083</td>
</tr>
<tr>
<td>7</td>
<td>0.079</td>
<td>0.076</td>
<td>0.082</td>
</tr>
<tr>
<td>8</td>
<td>0.078</td>
<td>0.075</td>
<td>0.082</td>
</tr>
<tr>
<td>9</td>
<td>0.078</td>
<td>0.074</td>
<td>0.081</td>
</tr>
</tbody>
</table>

Table 4: Effect of pH on metal-ion removal.

The Langmuir isotherm was adopted for the estimation of the maximum adsorption capacity corresponding to complete monolayer coverage on the biomass surface. The plots of specific sorption (C_e/q_e) against the equilibrium concentration (C_e) for Ni(II), Cu (II), and Zn(II) ions are as shown in figure 4 and the linear isotherm parameters, q_m, K_L, and the coefficient of determination R² are presented in Table 5. Langmuir equilibrium isotherm model was used to analyze the sorption of the three metals ion onto coconut fibre waste biomass. The R² values of the three metal ions indicate that the Langmuir isotherm provides a good model for the sorption system. The sorption capacity, q_m, which is a measure for the maximum adsorption capacity, corresponding to a complete monolayer coverage showed that the coconut fiber waste biomass has a higher capacity for Ni(II) (0.09g/g) and Zn(II) (0.09g/g) than Cu(II) (0.08g/g). The adsorption coefficient, K_L, which is related to the apparent energy of sorption was greater for Cu(II) (6.617Lg⁻¹) than Ni(II) (4.30Lg⁻¹) and Zn(II) (4.91Lg⁻¹). This observation showed that the energy of adsorption is not very favorable for Cu(II), probably due to its large ionic radius hence, not all binding sites would have been available to Cu(II). Similar sorption capacity orders have also been reported by [19] for different metal-ions onto fluted pumpkin waste biomass. This adsorption capacity is slightly higher than the adsorption capacities obtained for the three metals ions, using other biosorbents [23-25].

Furthermore, the favorability of adsorption of the three metal-ions onto the coconut fibre waste biomass was tested using the
An examination of the plot (Figure 5) reveals that the Freundlich divalent metals onto coconut fibre waste biomass are presented in Table 6. The linear Freundlich isotherm parameters for the sorption of the three adsorption intensity of the solute (metal-ion) onto the sorbent surface. Other biosorbent [19,26]. Based on the R² values, the linear form of the Langmuir isotherm model, expressed in terms of a dimensionless constant called the “Separation factor” [26]. The separation factor, S, is defined as expressed in Equation (4):

\[ S_F = \frac{1}{1 + K_F C_e} \]  

\[ C_e = \text{10mg/L} \]

The \( S_F \) indicates the shape of isotherm as follows:

- \( S_F > 1 \) Unfavourable isotherm
- \( S_F = 1 \) Linear Isotherm
- \( S_F = 0 \) Irreversible isotherm
- \( 0 > S_F < 1 \) Favourable isotherm

The separation parameters for the three metals are less than unity, indicating that the coconut fibre waste biomass is an excellent adsorbent for the three metal-ions. The observed separation factor (Table 6) and indicates that high concentration of Cu(II), Zn(II) and Ni(II) ions in an effluent will not be a limiting factor in the ability of coconut fibre waste biomass to sorb these metal-ions. Similar separation parameter favourability has been observed for the sorption of the metal ions using other biosorbent [19,26]. Based on the R² values, the linear form of the Langmuir isotherm appears to produce a reasonable model for the sorption of the three metals, since their R² values are all greater than 0.990, thus, showing that coconut fibre waste biomass is an excellent biomaterial for the removal of metal-ions from aqueous solution.

**Freundlich Isotherm**

The Freundlich isotherm model was chosen to estimate the adsorption intensity of the solute (metal-ion) onto the sorbent surface. The linear Freundlich isotherm parameters for the sorption of the three divalent metals onto coconut fibre waste biomass are presented in Table 6. An examination of the plot (Figure 5) reveals that the Freundlich isotherm was not a very appropriate model for the sorption study of the three metal-ions since the R² values of the three metals were all less than 0.900. The K, value of Zn(II) (0.880) is greater than that of Ni(II) (0.077) and Cu(II) (0.075), suggesting that Zn(II) has the greatest adsorption tendency towards the waste biomass than the other two metal-ions. The Freundlich equation parameter, \( \left( \frac{1}{n} \right) \), which is a measure of the absorption intensity for Zn(II) (0.071) is higher than those of Ni(II) (0.042) and Cu(II) (0.009), indicating a preferential sorption of Zn(II) by the waste biomass. Similar absorption intensities have been observed for the metal ions [26].

**Kinetics of Sorption**

This is probably the most important factor for determining the rate at which sorption takes place for a given system and is also very essential in understanding sorbent design, sorbate residence time and reactor dimension [19]. However according to [18], sorption kinetics shows a large range dependence on the physical and/or chemical characteristics of the sorbent materials, which also influences the sorption process and the mechanism.

**Pseudo-first order model**

A plot of ln(qe-qt) versus ln Ce (Figure 6) gives the pseudo-first order kinetics. From the plot, it is observed that the relationship between the metal ion diffusivity, ln Ce (Figure 6) and time, t, is non-linear, indicating that the diffusivity of the metal ion onto the biomass surface is film-diffusion controlled. The non linearity of the diffusivity plot showed that the first-order equation was not adequate for describing the adsorption of the three divalent metal ions onto the biomass surface. This trend has also been reported in [15] for the kinetic study of different ions onto caladium bicolor biomass. Also, it was observed that the pseudo-first order equation did not provide a very good description for the sorption of the three metal ions onto cocos mucifera biomass as, their R² were all less than 0.990 for all the three metal ions. Hence, no further consideration of this model was attempted. Table 7 shows the various determined kinetic parameters for the pseudo first order model.

**Pseudo-second order model**

The initial sorption rate, \( h_o \), the equilibrium sorption capacity,
The sorption of Ni(II), Cu(II) and Zn(II) onto coconut fiber waste biomass was found favorable. The kinetic data has provided information on the suitability of coconut fiber waste biomass as an excellent biosorbent for Ni(II), Cu(II) and Zn(II) from aqueous solution. The actual percent removal of the three metal ions from solution increased with increase in initial metal ion concentration. The equilibrium pH for the sorption of the three metal ions was 5. The sorption of the three metal ions was found to increase rapidly with contact time. The equilibrium data fit both the Langmuir and the Freundlich isotherms well with the Langmuir model showing a better fit. On the whole, the coconut fiber waste biomass has been proven to be a cost effective biosorbent for Ni(II), Cu(II) and Zn(II) from aqueous solution. The coconut fiber waste biomass has been proven to be a cost effective biosorbents for Ni(II), Cu(II) and Zn(II) from aqueous solution.

### Conclusions

The sorption of Ni(II), Cu(II) and Zn(II) onto coconut fiber waste biomass was found favorable. The kinetic data has provided information on the suitability of coconut fiber waste biomass as an excellent biosorbents for Ni(II), Cu(II) and Zn(II) from aqueous solution. The actual percent removal of the three metal ions from solution increased with increase in initial metal ion concentration. The equilibrium pH for the sorption of the three metal ions was 5. The sorption of the three metal ions was found to increase rapidly with contact time. The equilibrium data fit both the Langmuir and the Freundlich isotherms well with the Langmuir model showing a better fit. On the whole, the coconut fiber waste biomass has been proven to be a cost effective biosorbents for treating heavy metal-contaminated wastewater as an alternative to the available conventional methods.

### Table 8: Values of kinetic parameters for the pseudo-second order rate for the sorption of the three metal ions on the biomass.

<table>
<thead>
<tr>
<th>Metal ions</th>
<th>H (mgg⁻¹min⁻¹)</th>
<th>K (mgg⁻¹min⁻¹)</th>
<th>qe (mgg⁻¹)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni(II)</td>
<td>0.153</td>
<td>26.49</td>
<td>0.076</td>
<td>0.999</td>
</tr>
<tr>
<td>Cu(II)</td>
<td>0.331</td>
<td>62.11</td>
<td>0.07</td>
<td>0.998</td>
</tr>
<tr>
<td>Zn(II)</td>
<td>1.293</td>
<td>175.50</td>
<td>0.086</td>
<td>0.999</td>
</tr>
</tbody>
</table>

### Table 9: Comparison of coefficients of determination, R² for the pseudo-first (R₁²) and pseudo-second (R₂²) order rate models.

<table>
<thead>
<tr>
<th>Metal ions</th>
<th>R₁²</th>
<th>R₂²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni(II)</td>
<td>0.998</td>
<td>0.406</td>
</tr>
<tr>
<td>Cu(II)</td>
<td>0.999</td>
<td>0.268</td>
</tr>
<tr>
<td>Zn(II)</td>
<td>0.999</td>
<td>0.325</td>
</tr>
</tbody>
</table>

References


