Adsorption of Zn(II) and Cd(II) ions in batch system by using the *Eichhornia crassipes*


**ABSTRACT**

In this work, the displacement effects on the sorption capacities of zinc and cadmium ions of the *Eichhornia crassipes*-type biosorbent in batch binary system has been studied. Preliminary single metal sorption experiments were carried out. An improvement on the Zn(II) and Cd(II) ions removal was achieved by working at 30°C temperature and with non-uniform biosorbent grain sizes. A 60 min equilibrium time was achieved for both Zn(II) and Cd(II) ions. Furthermore, it was found that the overall kinetic data were best described by the pseudo second-order kinetic model. Classical multi-component adsorption isotherms have been tested as well as a modified extended Langmuir isotherm model, showing good agreement with the equilibrium binary data. Around 0.65 mequiv./g maximum metal uptake associated with the *E. crassipes* biosorbent was attained and the *E. crassipes* biosorbent has shown higher adsorption affinity for the zinc ions than for the cadmium ones in the binary system.

**Key words** | biosorption, isotherm models, metals

**INTRODUCTION**

The industrial treatments of wastewaters containing low concentration of heavy metals are still a challenge and serious environmental concern. Due to the heavy metals’ solubility and mobility, metal accumulation in the food chain has brought serious impact on human health. Heavy metals such as cadmium and zinc are one of the most toxic pollutants produced in the wastewaters from industrial processes. With regard to cadmium, it is commonly found in waste waters discharged from metal plating, metallurgical alloying, mining, dye synthesis, and battery production among others (Erosa et al. 2001; Luo et al. 2010). Meanwhile, zinc is one of the pollutants commonly found in the industrial effluents, which can be found in the discharge of the metallurgical, mining, and tailings ponds, as well as combustion ash, and wood preservatives and zinc-based fertilizers (Bayramoglu & Arca 2008; Mádenes et al. 2009a).

Nowadays, the biosorption technology is widely used in the removal of pollutants from the industrial effluent, allowing the pollutant to be transformed to a solid phase (adsorbent) and subsequently recovered by a desorption process and then stored in an environmentally secure place. Biosorption studies have been reported on algae (Schiewer 1999), fungus (Luo et al. 2010), orange peel (Fiorentin et al. 2010), activated carbon (Espinoza-Quiñones et al. 2010), and aquatic macrophytes (Espinoza-Quiñones et al. 2009; Mádenes et al. 2009b, 2010, 2011; Pietrobelli et al. 2009), where different conditions of sequestration and accumulation of metal ions have been applied.

The aim of this work was is to study the equilibrium and kinetic biosorption process, using *Eichhornia crassipes* as the biosorbent to stabilize the Cd and Zn ions from the aqueous medium. Adsorption tests were previously performed in order to investigate the effects of drying and solution temperatures, particle grain size, and pH on the performance of metal removal rate. Based on the best experimental conditions, adsorption equilibrium data for the Cd–Zn binary system were obtained and interpreted on the basis of a set of multi-component isotherm models. By applying the global particle swarm optimization (PSO) method, optimized adsorption parameter values were calculated.
MATERIALS AND METHODS

Chemicals and biosorbent

All chemicals used were analytical grade. Deionized water was used as a diluent. Stock solutions of zinc and cadmium ions were prepared using its salts (ZnCl₂ and CdCl₂·H₂O) in the range from 3.0 to 10.0 mequiv./L. 1 M-NaOH and 1 M-HCl solutions were used for pH adjustment. Zinc and cadmium certified standard solutions (1.0 g/L for AAS, Merck) were used to obtain the calibration curve for each liquid sample was measured by AAS and the and then the solid phase was separated from the liquid mixtures were agitated on a rotary shaker for 120 min and then the solid phase was separated from the liquid one using a filtration system. The metal concentration in it was measured by the AAS procedure.

AAS measurements

For the determination of cadmium concentrations, 0.004–1.8 mg/L diluted stock solutions were used, while for Zn concentration analysis, 0.005–1.6 mg/L diluted stock solutions were used for calibration curve AAS (AA 932-GBC, Analitica). For metal analysis, the liquid phase of the samples was first of all separated from the adsorbent by using a vacuum filtration system and then the concentrations of zinc and cadmium were determined with a calibration curve.

Preliminary tests

The effects of two drying temperatures of the biosorbent (30 and 50 °C) and grounded.

The effects of two drying temperatures of the biosorbent (30 and 50 °C) and grounded. Eichhornia crassipes plants were collected from natural shallow ponds in the west region of Brazilian Paraná state. The aquatic plants were washed with tap water and rinsed several times with deionized water, eliminating any remains of sediments and particles, and then they were separately dried at two temperatures (30 and 50 °C) and grounded.

The effects of two drying temperatures of the biosorbent (30 and 50 °C), solution temperature (ranging from 25–45 °C), biosorbent grain size (0.147, 0.295, and 0.589 mm) and with non-uniform biosorbent grain size, and solution pH (5–5 range) on the performance of biosorption processes were investigated in single metal adsorption systems (Zn or Cd ions). 250 mg dry biomass sample was added to 50 mL metal solution. In order to avoid the precipitation point for each metal, all solution pH values were below 5, according to Pietrobelli et al. (2009). The mixtures were agitated on a rotary shaker for 120 min and then the solid phase was separated from the liquid one using a filtration system. The metal concentration in each liquid sample was measured by AAS and the amount of adsorbed metal was calculated by using Equation (1).

\[
q_j^* = \frac{V(C_j^0 - C_j^*)}{m}
\]  

where \(q_j^*\) stands for concentration of species ‘j’ in the biosorbent (E. crassipes) at equilibrium (mequiv./g), \(C_j^0\) stands for concentration of species ‘j’ in the solution at equilibrium (mequiv./L), \(C_j^*\) is initial concentration of species ‘j’ in the solution (mequiv./L), \(V\) is the solution volume (L) and \(m\) is the biosorbent mass (g).

Kinetic and equilibrium experiments

Based on the results of the preliminary tests, biosorbent dried at 30 °C with non-uniform particle grain size was used for both kinetic and equilibrium experiments. Considering a set of short contact times (5, 10, 15, 30, 45, 60, 90 and 120 min), 25 mL of each metal solution with initial Zn(II) and Cd(II) ions concentrations of 4.0 mequiv./L was added to 250 mg dry biomass. Moreover, the mixtures were agitated on rotary shaker at 30 °C and the solution pH was adjusted to 5 as required. The liquid phase was separated from the solid one by filtration and then the metal concentration in it was measured by the AAS procedure.

Equilibrium experiments in duplicates at 30 °C solution temperature, pH 5 and 60 min contact time were carried out for single and binary metal sorption systems. For a single system, 50 mL solution containing around 4.0 mequiv./L metal concentration was added to the dry biomass, ranging from 20 to 550 mg. Especially, for a mixture of Zn(II) and Cd(II) ions, only 25 mL of each metal solution with equal initial Zn(II) and Cd(II) concentrations of around 4.0 mequiv./L was added to a range of 20 to 550 mg biomass. The liquid phase was separated from the solid one by filtration and then the metal concentration in it was measured by the AAS procedure.

Mathematical modeling

As the real geometry of the adsorbent particle is unknown or irregular, a simple mathematical equation such as described by Equation (2), namely pseudo-first order kinetic model, which was reported as linear driving force model by other researchers (Borba et al. 2006; Cruz et al. 2006), has been also applied in the present work for the analysis of the dynamics of heavy metal sorption.

\[
\frac{dt}{dC_j^*} = \frac{k_{ij}^* \cdot q_j^*}{V} \quad \text{for the analysis of the dynamics of heavy metal sorption}
\]
processes.

\[
\frac{dq_i}{dt} = k_i(q_i^m - q_i)
\]  

(2)

where \(k_i\) is the rate constant of the pseudo first-order adsorption process (min\(^{-1}\)); \(q_i\) is the concentration of species ‘\(j\)’ in the biosorbent at time \(t\), (mequiv. g\(^{-1}\)); and \(q_i^m\) is the concentration of species ‘\(j\)’ of the biosorbent in equilibrium with the concentration of the ‘\(n\)’ species in the solution, (mequiv. g\(^{-1}\)).

Our modeling approach for the description of Zn(II)–Cd(II) equilibrium biosorption process was based on several multi-component adsorption isotherm models such as Langmuir Equation (3), Langmuir–Freundlich Equation (4), Redlich–Peterson Equation (5) and Toth Equation (6). The details about these models can be found therein (Limousin et al. 2007).

\[
q_i^m = \frac{q_{\text{max}} b_i C_i^m}{1 + \sum_{i=1}^{\text{n}} b_i C_i^m}
\]  

(3)

\[
q_i^m = \frac{q_{\text{max}} b_i (C_i^m)^n}{1 + \sum_{i=1}^{\text{n}} b_i (C_i^m)^n}
\]  

(4)

\[
q_i^m = \frac{q_{\text{max}} b_i C_i^m}{1 + \sum_{i=1}^{\text{n}} b_i (C_i^m)^{\frac{1}{n}}}
\]  

(5)

\[
q_i^m = \frac{q_{\text{max}} b_i C_i^m}{(1 + \sum_{i=1}^{\text{n}} b_i (C_i^m)^{\frac{1}{n}})^{\frac{1}{m}}}
\]  

(6)

where \(q_i^m\) is the concentration of species ‘\(j\)’ on the biosorbent in equilibrium with the concentration of the ‘\(n\)’ species in the solution, (mequiv. g\(^{-1}\)); while \(b_i\) (g mequiv.\(^{-1}\)) and \(q_{\text{max}}\) (mequiv. g\(^{-1}\)) are isotherm parameters to be determined.

As parameter identification procedure, the Particle Swarm Optimization (PSO) method proposed by Kennedy & Eberhard (2001) has been applied and more details and their applications were reported therein (Trigueros et al. 200a, 201b). These PSO parameters settings (swarm of 2000 particles and 100 iterations) were enough to achieve a good convergence and optimal constants values. An objective function (OF), which was built-in on the basis of least square statistical method Equation (7), was applied, extracting a set of equilibrium or kinetic parameter values.

\[
\text{OF} = \sum_{i=1}^{M} \left[ \sum_{j=1}^{N} (q_{\text{exp}}^j - q_{\text{mod}}^j)^2 \right]
\]  

(7)

where \(q_{\text{exp}}^j\) and \(q_{\text{mod}}^j\) stand for experimental and model concentrations of species ‘\(j\)’ in biosorbent, respectively, \(N\) stands for number of the experimental points and \(M\) is the number of species.

### RESULTS AND DISCUSSION

#### Preliminary results

According to the biomass drying test, cadmium and zinc ion removal rates above 60% were achieved at a 30 ℃ drying temperature, whereas slightly smaller metal ion removal rates (55%) were achieved at a 50 ℃ drying temperature. In fact a high drying temperature might produce a pore size contraction on dry biomass surface, reducing thus the metal adsorption capacity. Based on the assumption that a smaller drying temperature would allow a reduction of overall costs, all adsorption experiments were performed at a 30 ℃ drying temperature.

Regarding the three particle grain and non-uniform particle grain sizes, it was observed that cadmium ion removal rate values were of 52, 51, 52 and 53% for 0.147, 0.295, 0.589 and grain size mixture, respectively, whereas a little higher zinc ion removal ones around 63% within a 5% standard deviation were also observed for the same considered grain sizes. In other words, the grain size effect might be considered as negligible within a 5% standard deviation and thus a mixture of non-uniform particle grain sizes was used at all posterior metal sorption experiments.

Considering the four solution temperatures, adsorption test results have shown that both cadmium and zinc divalent ions exhibit the same profile for its removal rate as a function of the solution temperatures. Moreover, lower removal rates around 54% for both metals were achieved, when 25 and 45 ℃ solution temperatures were considered, whereas, the highest metal removal rate (around 60%) was attained for 30 ℃ solution temperature for both metals. Therefore, the 30 ℃ solution temperature was chosen in order to improve the performance of metal adsorption process.

According to the metal speciation diagram done by the application of the software HYDRA (Hydrochemical...
Equilibrium-Constant Database), the main cadmium and zinc species in 8 mequiv./L Zn–Cd binary solution are expected to be Cd$^{2+}$ and Zn$^{2+}$ when pH values are below 7 and 6, respectively. Since above pH 5.5 the cadmium and zinc ions could precipitate in single metal solutions as reported by Pietrobelli et al. (2009), high pH values should be avoided in Zn–Cd binary adsorption experiments. Conversely, it was observed in the present work that cadmium and zinc ion removal rates were increased from 20 to 60% when solution pH values were increasing from 3 to 5. As reported by Zheng et al. (2009) about the sorption mechanism by using the Eichhornia crassipes as biosorbent, the sorption of Cu(II) is greatly affected by the variation of solution pH, but with a higher maximum capacity observed at an initial pH of 4.5, which the main copper species in solution is Cu$^{2+}$. In addition, water hyacinth roots have shown high adsorption capacity for copper ions at pH 4.0–6.5. Apart from that, Davis et al. (2003) and Verma et al. (2008) have suggested that carboxylic groups (–COOH) are the main adsorption sites on algae and macrophytes adsorbents. Moreover, such functional groups are expected to be deprotonated at 3.5–5.5 pH range, allowing attracting the positively charged metal ions by a typical coulombian interaction. Likewise as reported by Schiewer (1999), it is expected to create more sites free and easily available for metal binding at pH > 4. At best, a solution pH 5 could be attributed to a less available H$^{+}$ to compete with cadmium and zinc divalent ions for adsorption sites of biomass. Therefore, pH value of 5 was set up not only for kinetic experiments but also equilibrium ones in the present work, in order to improve the performance of metal adsorption process by using the E. crassipes adsorbent.

**Kinetic results**

From the Zn(II)–Cd(II) binary sorption kinetic data analysis (see Figure 1), a 60 min equilibrium time was observed with 46.8 and 20.8% removal values for Zn(II) and Cd(II) ions, respectively. This different response might be associated to the different physical/chemical properties, such as the ionic radius (0.83 and 0.95 Å for Zn and Cd ions, respectively) existing between metallic ions in a sorption process or other ones on the biosorbent surface, as suggested by Covelo et al. (2007).

Under similar experimental conditions, a 240 min equilibrium time and 60 and 30% removal rates for Zn(II) and Cd(II) ions, respectively, were reported by Fan et al. (2008) by using the Penicillium simplicissimum biosorbent. While, Vilar et al. (2008) for the Cd/Zn system ([Cd] = 0.854 mmol/L and [Zn] =1.35 mmol/L) by using Algae Gelidium as biosorbent have observed a 20 min equilibrium time as well as 40 and 60% removal rates of cadmium and zinc, respectively.

By the application of the pseudo-first order kinetic model, rate constant ($k_f$) values of 0.15 and 0.17 min$^{-1}$ for cadmium and zinc ions, respectively, were obtained with good agreement (OF = 0.0104) for the kinetic data (see Figure 1), suggesting that the metal adsorption affinity order is the following Zn > Cd.

**Equilibrium**

By combining different biosorbent mass and metal iso-concentration values and using a 30 °C solution temperature and a 60 min equilibrium time, equilibrium adsorption data for Zn(II)–Cd(II) binary system were obtained at pH 5. As a representation of the metal binary adsorption data, 3D metal adsorption surfaces were built (see Figure 2) where the metal uptake responses are plotted in $z$-axis and the equilibrium concentrations of zinc and cadmium ions in $x$- and $y$-axis.

By the application of the PSO method to equilibrium adsorption data, the estimated adsorption parameter values for the set of isotherm models Equations (3)–(6) were obtained as summarized in Table 1. It must be noted that for single and binary systems the specific adsorption fitting parameter value, namely $m$ of the Redlich-Peterson and Toth isotherm models, are equal to one, reducing all of them to the same Langmuir-type one. Besides, the Langmuir model has provided the best fitting of the equilibrium data for Zn(II) and Cd(II) ions in order to characterize the E. crassipes biomass as the metal adsorbent; followed by the Langmuir–Freundlich model. However, as reported in
other work (Papageorgiou et al. 2009), in many cases the adsorption constants of the individual isotherms fail to describe the interactions between metal ions in multi-component systems. For this reason, further correction parameters to the classical competitive Langmuir equation are introduced in order to make the model capable to depict the complexity of the adsorption process. In the present work, the modified extended Langmuir equation that is described by the Equation (8) has been applied to fit the Zn–Cd binary adsorption data.

\[
q_{\text{eq},i} = q_{\text{max},i} \left( \frac{(b_i^L/n_i^L)C_{\text{eq},i}}{1 + \sum_{j=1}^{N} (b_j^L/n_j^L)C_{\text{eq},j}} \right)
\]

where \(q_{\text{eq},i}\) (mequiv. g\(^{-1}\)) is the metal uptake of the component \(i\), \(N\) is the number of the components, \(C_{\text{eq},j}\) (mequiv. L\(^{-1}\)) is the equilibrium concentration of each component \(j\), while \(b_i^L\) (g mequiv. \(^{-1}\)) and \(q_{\text{max},i}\) (mequiv. g\(^{-1}\)) are Langmuir parameters to be determined, \(n_i^L\) is the correction parameter of species \(i\), which is characteristic of each species and depends on the concentrations of all the other components in the solution.

As can be seen in Figure 2 the modified extended-to-multi-component Langmuir model exhibits a good reproduction of the single and binary data for the whole concentration range by using the \(E.\) crassipes. In addition, it must be noted that the single metal isotherms of each metal can be seen in the respective main vertical planes, where the concentration of the other metal is zero, predicting thus the single metal adsorption points and its corresponding maximum capacity. Within the modeling of both single and binary adsorption data, the values of the maximum adsorption capacities \(q_{\text{max},i}\) and affinity parameter \(b_i^L\) for Zn(II) and Cd(II) ions were kept the same as those obtained from the modeling results of the single adsorption data. It was observed that Cd(II) adsorption capacity is slightly higher than the Zn(II) adsorption. As the PSO-based predicted results are in good agreement with the equilibrium experimental data according to the indicators of the goodness of fit, namely OF and \(r^2\) (see Table 1), the PSO method showed a satisfactory parameter identification procedure.

According to the modified extended Langmuir sorption model, the presence of other metals in the solutions might affect the shape of the isotherm curve, due to changes in apparent metal affinity for the active sites. Regarding the value of correction parameter of species \(i\) \((n_i^L)\), if the biosorbent has different affinity between both metal ions then different \(n_i^L\) values are expected to be predicted by the proposed model, instead of \(n_i^L\) ones equals to one. The estimated values of correction parameter of species \(i\) \((n_i^L)\) were 0.644 and 1.358 for Zn and Cd, respectively. Analyzing the predicted results, it is observed that the ratio of affinity to correction parameters \((b_i^L/n_i^L)\) were 0.826 and 0.417 for Zn and Cd ions, respectively, indicating that the affinity of Zn(II) is higher than Cd(II) in the binary adsorption system.

Analyzing the predicted metal capacity values under isometric concentration condition, it can be assigned to the \(E.\) crassipes biosorbent (Figure 2) a maximum Zn(II) capacity value of 0.469 mequiv. g\(^{-1}\), which is higher than that for Cd(II) ion (0.178 mequiv. g\(^{-1}\)). In addition, a sum of these predicted maximum metal capacities (0.647 mequiv. g\(^{-1}\)), namely the total metal capacity, resembles those obtained in single metal adsorption systems (0.633 and 0.677 mequiv. g\(^{-1}\)).
The total metal capacity, which involves all available metal adsorption sites on the biosorbent surface, is mainly depending on the type of biosorbent (Módenes et al. 2011), i.e., its physical/chemical properties and is totally independent of the mixture of metals with different concentrations.

Based on the extended modified Langmuir isotherm model and the PSO method results, binary adsorption isotherm data have been effectively predicted and their parameters better estimated, suggesting that the Zn(II) and Cd(II) ions in binary component mixtures behave dependently of each other, with competition, interaction, or displacement effects.

**CONCLUSIONS**

Batch tests have shown that pH 5 and 30 °C solution temperature are the best experimental conditions to adsorb metal divalent ions onto the sorbent surface. The chosen grain size range showed an insignificant influence on the metal ions removal process. The short equilibrium time around 60 min suggests that the dry *E. crassipes* biomass can be considered as an attractive alternative in adsorption continuous treatment systems. By the application of the pseudo-first order kinetic model, rate constant (*k*₁) values of 0.15 and 0.17 min⁻¹ for cadmium and zinc ions, respectively, were obtained. The equilibrium Zn(II)–Cd(II) binary data have been well described by the extended modified Langmuir isotherm model with their parameters well estimated by applying the PSO method. A 0.65 mequiv. g⁻¹ maximum uptake associated to the *E. crassipes* biomass was obtained. The adsorption results showed that *E. crassipes* exhibited higher affinity for the zinc ions than for the cadmium ones. Finally, the *E. crassipes* biomass exhibited a good performance on the zinc and cadmium ions removal from aqueous medium, and was considered to be an attractive biosorbent alternative for industrial wastewater treatment application.

**ACKNOWLEDGEMENTS**

We thank the Araucaria Foundation for financial support of this study.

---

**Table 1** | Metal adsorption modeling parameters and their respective fitting statistical parameters for the set of multi-component tested isotherm models corresponding to the Zn–Cd adsorption data (pH 5, 30 °C and 60 min equilibrium time)

<table>
<thead>
<tr>
<th>Isotherm</th>
<th>Parameters</th>
<th>Metal ion</th>
<th>Zn(II)</th>
<th>Cd(II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langmuir</td>
<td><em>q</em>ₘₐₓ (mequiv. g⁻¹)</td>
<td>0.633 ± 0.054</td>
<td>0.667 ± 0.036</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>b</em> (L mequiv.⁻¹)</td>
<td>0.532 ± 0.116</td>
<td>0.566 ± 0.078</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>r</em>²</td>
<td>0.9360</td>
<td>0.9453</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OF</td>
<td>0.29826</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Langmuir–Freundlich</td>
<td><em>q</em>ₘₐₓ (mequiv. g⁻¹)</td>
<td>0.632 ± 0.016</td>
<td>0.659 ± 0.025</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>b</em> (L mequiv.⁻¹)</td>
<td>0.530 ± 0.052</td>
<td>0.566 ± 0.078</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>M</em></td>
<td>0.881</td>
<td>0.881</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>r</em>²</td>
<td>0.9389</td>
<td>0.9431</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OF</td>
<td>0.29937</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redlich–Peterson</td>
<td><em>q</em>ₘₐₓ (mequiv. g⁻¹)</td>
<td>0.637 ± 0.054</td>
<td>0.668 ± 0.036</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>b</em> (L mequiv.⁻¹)</td>
<td>0.532 ± 0.117</td>
<td>0.566 ± 0.078</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>M</em></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>r</em>²</td>
<td>0.9360</td>
<td>0.9453</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OF</td>
<td>0.29826</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toth</td>
<td><em>q</em>ₘₐₓ (mequiv. g⁻¹)</td>
<td>0.633 ± 0.015</td>
<td>0.667 ± 0.031</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>b</em> (L mequiv.⁻¹)</td>
<td>0.532 ± 0.048</td>
<td>0.566 ± 0.065</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>M</em></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>r</em>²</td>
<td>0.9360</td>
<td>0.9453</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OF</td>
<td>0.29826</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified extended Langmuir</td>
<td><em>q</em>ₘₐₓ (mequiv. g⁻¹)</td>
<td>0.633 ± 0.015</td>
<td>0.667 ± 0.025</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>b</em> (L mequiv.⁻¹)</td>
<td>0.532 ± 0.030</td>
<td>0.566 ± 0.040</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>N</em></td>
<td>0.644</td>
<td>1.358</td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>r</em>²</td>
<td>0.9752</td>
<td>0.9852</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OF</td>
<td>0.07951</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES


First received 16 March 2011; accepted in revised form 5 July 2011