

Recovery of nickel and cobalt from organic acid complexes: Adsorption mechanisms of metal-organic complexes onto aminophosphonate chelating resin

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Abstract

This study examined the recovery of nickel and cobalt from organic acid complexes using a chelating aminophosphonate Purolite S950 resin. These metal complexes are generated by bioleaching nickel laterite ores, a commercial nickel and cobalt mineral oxide, with heterotrophic organism and their metabolites or organic acid products. Equilibrium adsorption tests were conducted as a function of Ni and Co concentrations (15–2000 mg/L), solution pH (0.01 and 0.1 M acids) and three metabolic complexing agents (citrate, malate and lactate). It was shown that the adsorption of the various Ni- and Co-complexes on Purolite were quite low, 16–18 and 5.4–9 mg/g of resin, respectively, in comparison to the smaller nickel ions and nickel sulfate. This was attributed to the bulky organic ligands which promoted crowding effect or steric hindrance. The adsorption of these complexes was further hampered by the strong affinity of the resin to H⁺ ions under acidic conditions. Mechanisms of adsorption, as inferred from the fitted empirical Langmuir and Freundlich models, were correlated to the proposed steric hindrance and competitive adsorption effects. Nickel and cobalt elution from the resin were found to be effective and were independent of the type of metal complexes and metal concentrations. This study demonstrated the relative challenges involved in recovering nickel and cobalt from bioleaching solutions.

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1. Introduction

Biological leaching of low-grade nickel laterite ore is based on a non-traditional leaching of oxide minerals using heterotrophic or fungi microorganisms including *Aspergillus* and *Penicillium* strains and their metabolic products (organic acids). In this process, organic acids produced by the metabolism of the fungi organisms, solubilise metals from oxide minerals to form metal organic complexes [1]. Among the various organic acids produced, citric, malic and lactic acids have been found the most effective in dissolving the desired metals (Ni and Co) from low-grade nickel laterite ores [2]. Although the amenability of nickel laterite to this bioleaching process has been demonstrated, studies of Ni and Co recovery from the resulting metal-organic complexes appear scarce.

Metal recovery from solution is typically achieved by techniques including chemical precipitation [3,4], solvent extraction [5,6] and adsorption [7–13]. Adsorption is conducted using adsorbents including activated carbon [7] and ion-exchange resins [8,9]. Although activated carbons are useful in removing organic solutes from solution, they are often not as effective in recovering metals from solutions in comparison to ion-exchange resins. Various types of ion-exchange resins are commercially available and are differentiated by their surface functional groups and nature of adsorption. These include cationic, anionic and chelating resins. Adsorption using chelating resins has found wide use in industry, in particular for heavy metal ion removal [10,11]. Chelating resins are specially oriented ionic and non-ionic groups that are capable of exhibiting high adsorption selectivities and operating capacities. It is therefore not unusual to find that chelating resins have greater success in recovering metals from complex solutions in comparison to cation-exchange resins [12]. Commercial chelating resins, for example Dowex M4195, Amberlite IRC748, Ionac SR-5 and Purolite S930, have been

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used to recover nickel and cobalt successfully from sulfate solutions [13].

To date, the recovery of nickel and cobalt from bioleaching solutions by adsorption, has been hampered by the stability of metal-organic complexes. Basically this means the metal-organic complexes will adsorb on the resin surface without dissociating. This restriction must be clearly elucidated to enable proper design and evaluation of metal recovery systems from the nickel laterite bioleaching process. Some work has examined the recovery of metals from organic acid complexes using ion-exchange resins, however, most have been conducted in-house in industry. Most of these results have been reported only in patents [14] and a few results have reached the open literature. Often the limited results that been reported provide little basis to understand the fundamental aspects of the adsorption process. An understanding of equilibrium and kinetics of adsorption is essential in design of adsorption units suitable for recovering metals from leaching operation of interest in this study. In this study, we examined the nature of the adsorption of nickel- and cobalt-organic complexes using an aminophosphonic Purolite S950 chelating resin. Purolite S950 has been shown to have a high affinity for various heavy metals and its successful application in metallurgical and wastewater treatment processes have been encouraging [15,16]. A series of adsorption tests were therefore conducted to establish the equilibrium adsorption isotherms of Ni- and Co-complexes on Purolite S950. The effects of variables including the type of complexing agents, metal concentration and pH on the adsorption capacity, selectivity, adsorption mechanism and desorption properties of the resins were considered. To investigate the mechanism of adsorption, the adsorption data were fitted to the Langmuir and Freundlich models.

2. Experimental

2.1. Materials

2.1.1. Resins

The properties of Purolite S950 (Purolite International Co., Ltd.) are listed in Table 1. Purolite S950 is a macroporous polystyrene-based chelating resin with an aminophosphonate functional group (see Fig. 1). The resin was received in sodium (Na^+) form. Prior to use, the resin was converted to the hydrogen

Table 1
Properties of commercial chelating resin for selective sorption of Ni and Co [17]

	Purolite S950
Matrix	Macroporous styrene-divinylbenzene
Functional group	Aminophosphonic acid
Particle size (mm)	0.3–1.2
Bed density (g/L)	710–745
Particle density (g/cm ³)	1.13
Moisture content (%)	60–68
Operating temperature, max (°C)	90
pH range (operating)	H ⁺ form 2–6, Na ⁺ form 6–11

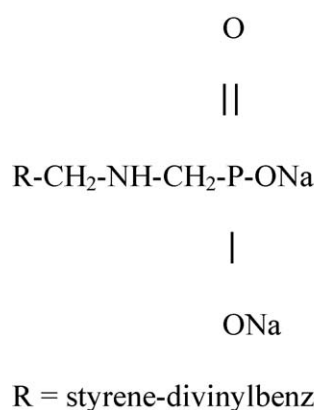


Fig. 1. Structure of an aminophosphonate chelating resin [17].

(H⁺) form by washing it in 2 M HCl followed by further washing in deionised water. The resin regeneration procedures follow the recommendations provided by the manufacturers [17]. The resin-H was dried and kept at room temperature in a desiccator until it was used.

2.1.2. Metal complexes

Synthetic bioleaching solutions were prepared using analytical-grade reagents; Ni(NO₃)₂·6H₂O and Co(NO₃)₂·6H₂O Sigma–Aldrich metal salts and citric, DL-malic and lactic organic acids (Bonnet, Australia). Metal solutions with concentrations from 15 to 2000 mg/L were prepared using 0.01 and 0.1 M of organic acid solutions. These concentrations are typical of the acids produced by fungi microorganisms [1,18]. Acid concentrations of 0.01 and 0.1 M typically generated solution pH of 2.2 and 1.8 in citric acid, 2.8 and 2.0 in malic and 2.6 and 1.9 in lactic acids.

2.2. Batch adsorption

Batch adsorption tests were conducted in 250 mL continuously stirred tank reactors at room temperature. One hundred milliliter of the metal solution with 2 g of dry resins were agitated at 120 rpm in an incubator shaker for 24 h. This period was sufficient to achieve adsorption equilibrium. Initial and equilibrium concentrations of metal solutions were determined using a Varian SpectroAA atomic absorption spectrophotometer using standard procedures. The amount of metal adsorbed per unit mass of resin was calculated from:

$$Q_e = \frac{C_i - C_e}{m} V \quad (1)$$

where C_i and C_e are the initial and equilibrium metal concentrations (mg/L), m the mass of resins (g) and V is the volume of the metal-organic complex solutions (L). The metals adsorbed on the resins were desorbed using 2 M nitric acid for 3 h under similar conditions used in the adsorption tests. Regeneration efficiencies were determined from the mass ratio of metal desorbed to that adsorbed by the resin at equilibrium.

3. Equilibrium isotherms

3.1. Adsorption isotherm models

Practical operations require the equilibrium correlations of the experimental adsorption data to empirical correlations which can include Langmuir [19] and Freundlich [20] models. Langmuir isotherm [19] is based on the assumption that all sorption sites on a structurally homogeneous adsorbent are identical and energetically equivalent. The basic idea behind the Langmuir model is the coverage of the surface by a monomolecular layer. Theoretically, the sorbent has a finite capacity for the sorbate, therefore, the saturation value is reached when no further sorption can take place. The Langmuir model is represented by the following equation:

$$Q_e = \frac{Q_m b C_e}{1 + b C_e} \quad (2)$$

where Q_m is a constant related to the area occupied by a monolayer of adsorbate and reflects the adsorption capacity (mg/g) of the adsorbent and b is a direct measure of adsorption intensity (L/g). A linearised form of Eq. (2) is:

$$\frac{1}{Q_e} = \frac{1}{Q_m b C_e} + \frac{1}{Q_m} \quad (3)$$

A plot of $1/Q_e$ versus $1/C_e$ yields a straight line if the adsorption data conforms to the Langmuir model. Values of Q_m and b are determined from the slope and intercept of the plot.

The Freundlich isotherm [20] is a specific case of the Langmuir model that describes adsorption based on heterogeneous surface energy. The energy varies with surface coverage a result of different sorption. The empirical Freundlich equation is represented by the following equation:

$$Q_e = A C_e^{1/n} \quad (4)$$

The constant A is an approximate indicator of the adsorption capacity (mg/g) and $1/n$ is related to adsorption intensity. The linearised form of Eq. (4) is:

$$\log Q_e = \log A + \frac{1}{n} \log C_e \quad (5)$$

A linear form of the Freundlich equation yields the constants A and $1/n$ from the intercept and slope of a plot of $\log Q_e$ versus $\log C_e$. The magnitude of $1/n$ is directly correlated to the efficiency of adsorption. Values from $0 < 1/n < 1$ are indicative of favorable adsorption.

3.2. Analysis of isotherm data

In this single component isotherm study, error functions based on non-linear Chi-square (χ^2) and coefficient of determination (R^2) were defined to enable the evaluation of the fit of the experimental data to the isotherms. The Chi-square equation is expressed as:

$$\chi^2 = \sum \frac{(Q_e - Q_{e,m})^2}{Q_{e,m}} \quad (6)$$

where Q_e is the experimental equilibrium adsorption capacity (mg/g) and $Q_{e,m}$ is the capacity predicted by the fitted model (mg/g). Greater agreement between predicted and experimental adsorption data results in lower χ^2 values. The coefficient of determination is defined as follows:

$$R^2 = \frac{SSR}{SST} \quad (7)$$

where SSR is the sum of square of regression and SST is the sum of square total. These are calculated from the number of fitted data (n) using the following equations:

$$SST = \sum_{i=1}^n (Q_{\text{measured}} - Q_{\text{mean}})^2 \quad (8)$$

$$SSR = \sum_{i=1}^n (Q_{\text{predicted}} - Q_{\text{mean}})^2 \quad (9)$$

Q_{mean} is mean of the experimental adsorption capacities. Values of R^2 vary from 0 (model does not account for the variability) to 1 (model accounts for all data variability).

4. Results and discussion

4.1. Adsorption of nickel organic complexes

Equilibrium adsorption isotherms of nickel-complexes, prepared using 0.01 and 0.1 M acids, are shown in Figs. 2–4. The dependence of nickel adsorption on the type of ligands and acid concentrations (or solution pH) is examined in these data. The equilibrium isotherms of the various nickel complexes were fitted to the Langmuir and Freundlich models. The solid and dashed lines in Figs. 2–4 are predicted by Freundlich and Langmuir models, respectively. Table 2 lists the estimated constants from the fitted models and the corresponding measures of fit (R^2 and χ^2 values) of the adsorption data. Evidently, the adsorption of the nickel complexes fit the Freundlich model. The R^2 and χ^2 values for the Freundlich model reported in Table 2 confirm this fit. The R^2 values for the Freundlich model varied from 0.96 to 0.99 compared to 0.92–0.96 for the Langmuir model. Similarly the χ^2 values for the Freundlich model, which varied from 0.08 to 0.43, are lower compared to Langmuir model which had χ^2 values from 1.27 to 4.52. This suggests the adsorption of nickel complexed to citrate, malate and lactate ligands, onto Purolite S950, occurs by multilayer adsorption. The Freundlich parameter, A values, reported in Table 2, reflects the effect of the type of ligands and solution pH (organic acid concentration) on the adsorption capacity of the nickel complexes.

The A values, in Table 2, suggest the order of adsorption capacity of the nickel complexes, at both 0.01 and 0.1 M acid concentrations is lactate > malate > citrate complexes. This order is confirmed by the corresponding $1/n$ values. The sizes of the ligands are in the following order; the lactate ($C_3H_5O_3^-$) is the smallest followed by malate ($C_4H_5O_5^-$) and citrate ($C_6H_7O_7^-$). It is therefore likely that the size of the ligands played a role in the order of the nickel complex adsorption, where the adsorption capacity of the nickel complexes was influenced by the steric hin-

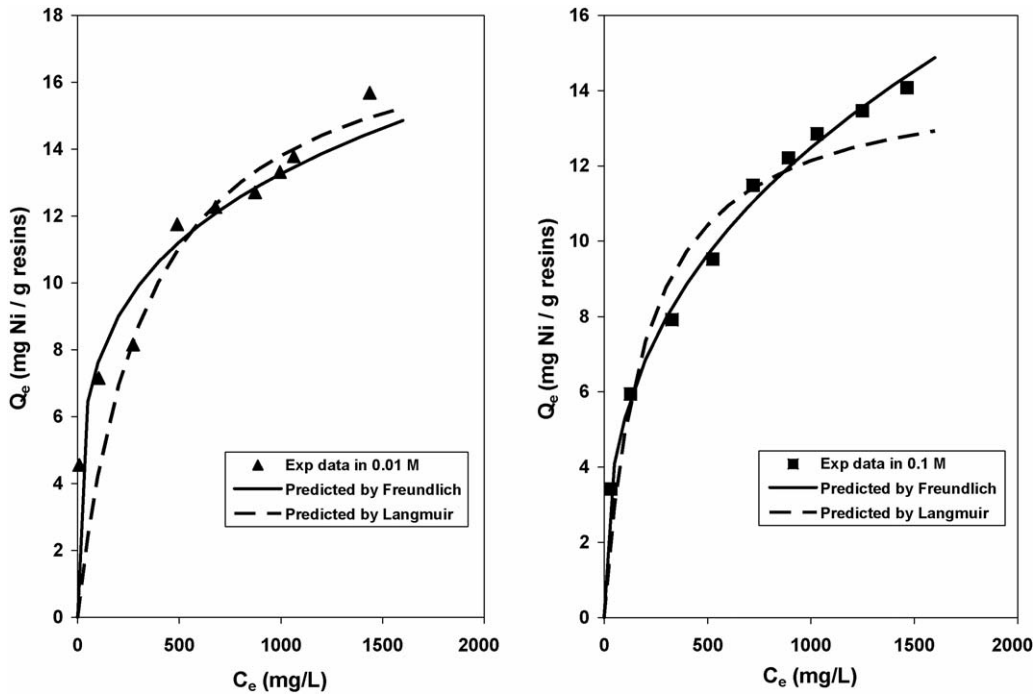


Fig. 2. Adsorption of Ni-citrate complexes on Purolite S950: in 0.01 M (left) and in 0.1 M acids (right).

drance or the crowding effect associated with the comparative bulkiness of the organic acid ligands in the nickel complexes. In general, the adsorption of all the nickel-organic acid complexes are all low in comparison to nickel from aqueous solutions and nickel complexed with smaller anions like sulfate. Nickel citrate, malate and lactate complexes, prepared using 0.01 M acids, have low *A* values from 2.51 to 3.26 mg/g (see Table 2). In comparison, nickel adsorbed from an aqueous solution using an IRN77

cation-exchange resin (based on sulfonic acid functional group) has an *A* value of 81.82 mg/g [21]. It would appear the bulkiness of the organic ligands hampers the uptake on the metal complexes on the resin.

The adsorption mechanism of nickel ions and nickel complexed to smaller anions like sulfate are predicted by the Langmuir model. Nickel sulfate adsorbed on Dowex M4195 ($Q_m = 94.51 \text{ mg/g}$ and $b = 2.54 \times 10^{-3} \text{ L/g}$, Amberlite IRC748

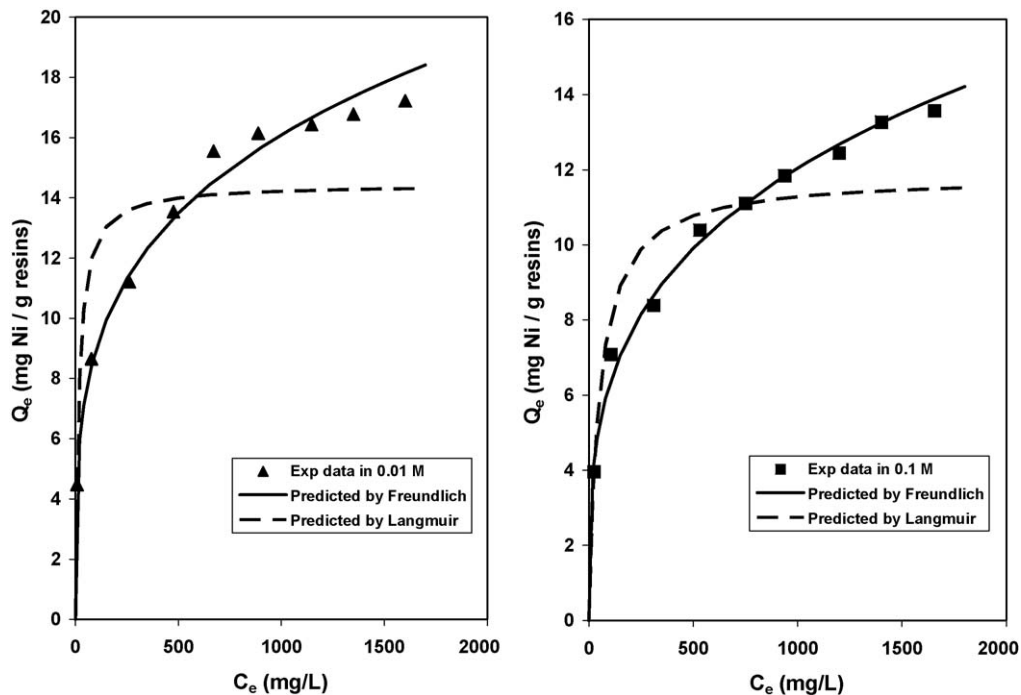


Fig. 3. Adsorption of Ni-malate complexes on Purolite S950: in 0.01 M (left) and in 0.1 M acids (right).

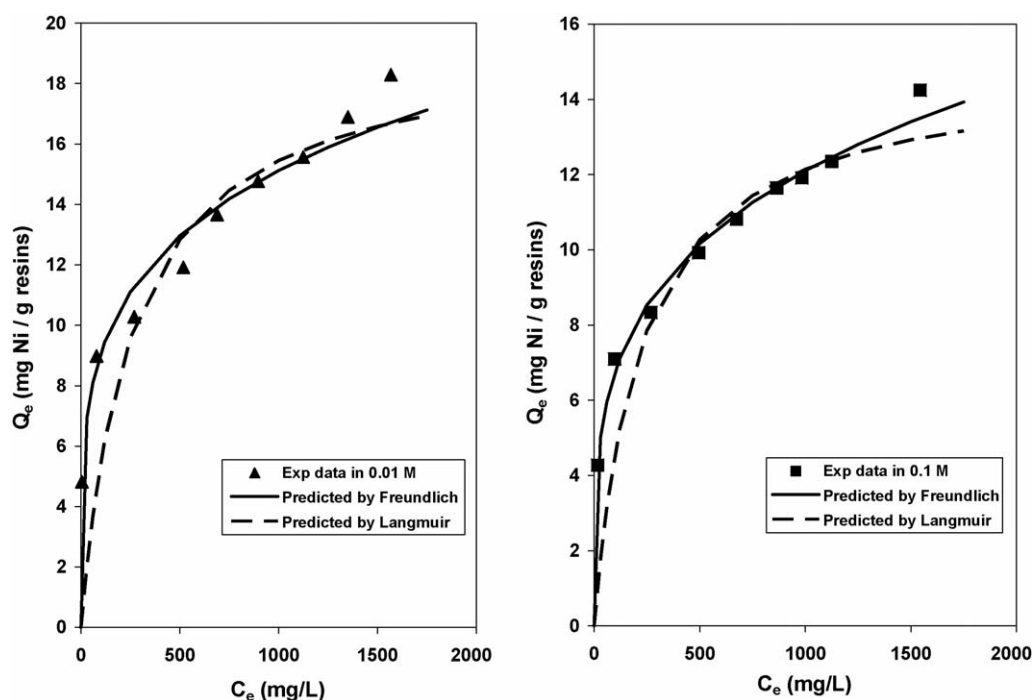


Fig. 4. Adsorption of Ni-lactate complexes on PuroLite S950: in 0.01 M (left) and in 0.1 M acids (right).

($Q_m = 125.03$ mg/g and $b = 1.22 \times 10^{-3}$ L/g) and Ionac SR-5 ($Q_m = 79.26$ mg/g and $b = 5.15 \times 10^{-3}$ L/g) have been shown to fit the Langmuir model [13]. In comparison, the adsorption of nickel complexed to the bulkier organic ligands, as shown in Table 2, are predicted by the Freundlich model. In addition, the monolayer adsorption of the smaller nickel sulfate complexes and ions corresponds to higher adsorption capacities in comparison to adsorption of nickel-organic acid complexes onto the PuroLite S950 (see Table 2). These results suggest that the crowding effect imparted by the larger organic acid ligands on nickel hampers the adsorption of the nickel-organic acid complexes on the resins and promotes multilayer adsorption. Whereas the smaller metal cation (Ni^{2+}), the hydrated nickel ions or NiSO_4 complex, which do not suffer from steric hindrance are adsorbed as a monolayer. Similar behaviour has been observed in the adsorption of nickel complexed to EDTA on Amberlite IRA-68. Poorer adsorption of the nickel-EDTA complex was obtained ($Q_m = 22$ mg/g) because of the bulky EDTA ligand [22]. These results reflect the challenges in recovering metals from metal-organic complexes.

Organic acid ligands like citrate, malate and lactate are also known to form very strong complexes with nickel in comparison to sulfate and hydroxyl anions [23]. The log formation constants, for example, of citrate (Cit) complexes; NiCit^{-1} , NiHCit and NiH_2Cit^+ are 6.7, 10.5 and 12.9, whereas the formation constant of NiSO_4 is 2.3 and $\text{Ni}(\text{OH})^+$, $\text{Ni}(\text{OH})_2$ and $\text{Ni}(\text{OH})_3^-$ are 4.1, 9 and 12.0, respectively. The stability of the nickel citrate complexes suggest ion-exchange separation of nickel is less likely to occur. The stability of the nickel-organic acid complexes and their bulkiness presents practical challenges in the recovery of nickel from bioleaching solutions.

Nickel complexes, prepared using the lower acid concentration (0.01 M), are shown to demonstrate higher adsorption capacities (higher A values) compared to those prepared from 0.1 M acids. The corresponding lower $1/n$ values for adsorption of complexes prepared using 0.01 M in comparison to 0.1 M acids supports the effective adsorption at the lower acid concentrations. It is known that PuroLite S950 is a weakly acidic chelating exchanger that rarely dissociates hydrogen ions in acidic solution [24,25]. The lower metal uptake with increasing

Table 2
Adsorption isotherm parameters for nickel organic complexes adsorbed onto PuroLite S950

Acids	Concentration of acid (M)	Langmuir constants				Freundlich constants			
		Q_m (mg/g)	b (L/g)	R^2	χ^2	A (mg/g)	$1/n$	R^2	χ^2
Citric	0.01	18.42	3.0×10^{-3}	0.96	1.91	2.51	0.24	0.96	0.43
	0.1	14.51	5.1×10^{-3}	0.93	1.49	0.95	0.37	0.99	0.06
Malic	0.01	14.45	6.2×10^{-2}	0.92	3.13	2.79	0.25	0.99	0.18
	0.1	11.83	2.0×10^{-2}	0.95	1.27	1.72	0.28	0.99	0.12
Lactic	0.01	19.42	3.9×10^{-3}	0.92	4.52	3.26	0.22	0.98	0.40
	0.1	14.84	4.5×10^{-3}	0.95	1.64	2.13	0.25	0.99	0.08

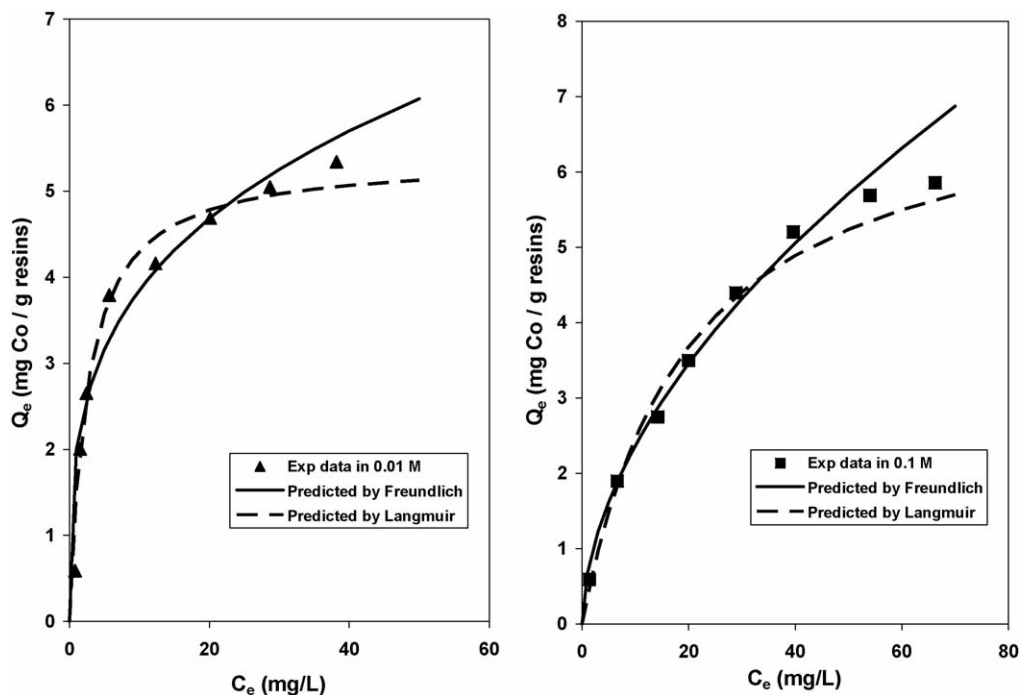


Fig. 5. Adsorption of Co-citrate complexes on Purolite S950: in 0.01 M (left) and in 0.1 M acids (right).

acid concentration would therefore be associated with the greater competition of hydronium ion (H^+) with metal complexes for adsorption sites. Reported order of selectivity of aminophosphonate chelating resins for various ions: $H^+ > Co^{2+} > Ni^{2+}$ [26] under acidic conditions further supports this stronger affinity of the resin to hydronium ions in comparison to the metal complexes. These results suggest that metal recovery using Purolite S950 should be conducted under weakly acidic solutions.

4.2. Adsorption of cobalt organic complexes

Equilibrium adsorption isotherms of cobalt complexes are shown in Figs. 5–7. Table 3 lists the corresponding fitted model parameters and the measures of fit, R^2 and χ^2 . Further examination of the results in Table 3 and Figs. 5–7 suggest the adsorption behaviours observed for Co-complexes are consistent with that obtained for the corresponding Ni-complexes. Higher adsorp-

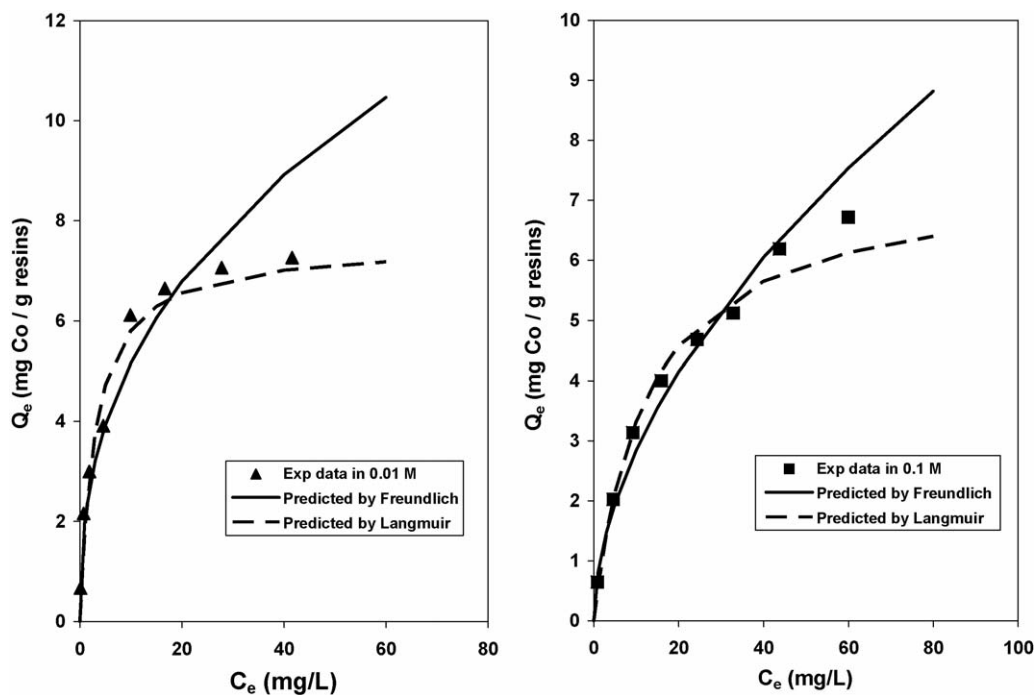


Fig. 6. Adsorption of Co-malate complexes on Purolite S950: in 0.01 M (left) and in 0.1 M acids (right).

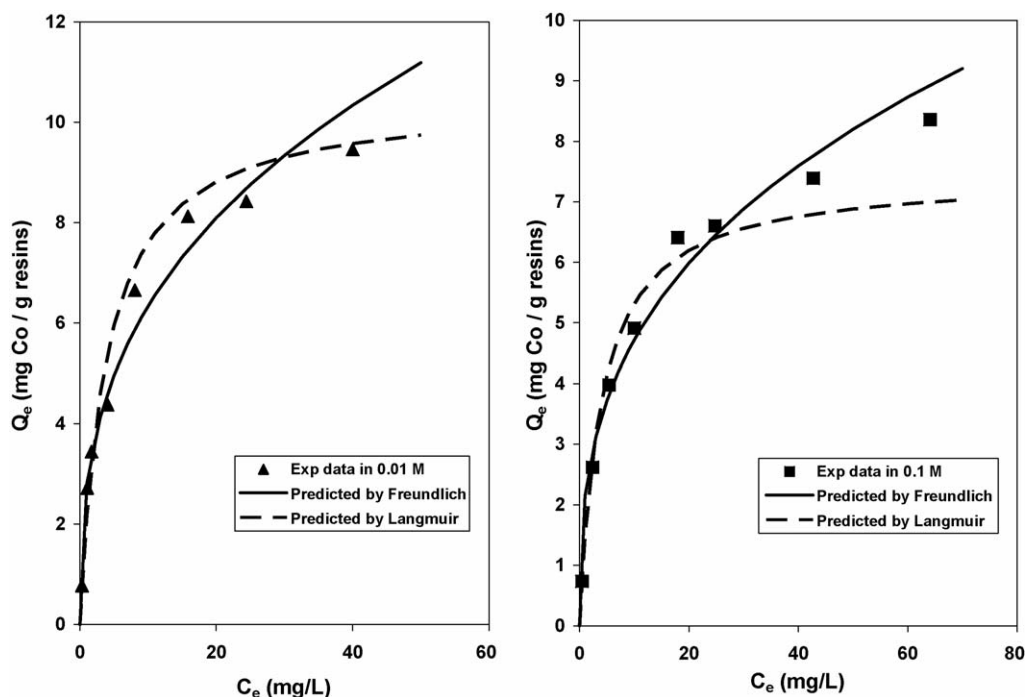


Fig. 7. Adsorption of Co-lactate complexes on Purolite S950: in 0.01 M (left) and in 0.1 M acids (right).

tion capacities were obtained under the weakly acidic conditions and the relative order of adsorption for the various complexes is lactate, malate and citrate. Similarly comparison of the adsorption capacities of Co-organic acid complexes were shown to be generally lower in comparison to their smaller counter parts, cobalt ion and cobalt sulfate [21]. The adsorption capacities of cobalt ions from aqueous solution on IRN77 resin (reflected by measured Freundlich parameters A , 75.63 mg/g) [21] is higher in comparison to cobalt organic complexes in Table 3. The effect of the size on ligands complexed to cobalt on the relative affinity of Co-complexes on the resin is similar to that observed for nickel, that is lactate > malate > citrate.

These results suggest the factors which influences the Ni- and Co-complex adsorption are similar. This also lends further support to the proposed effect of the bulkiness of the organic ligands or crowding effects that promote multilayer adsorption and steric hindrance, which hampers Co-complexes adsorption. At the more acidic conditions, although the Co-complexes adsorption occur to some extent, the higher affinity of the resin to H^+

under these condition [24–26] promotes lower adsorption of the Co-complexes.

The Co-complexes adsorptions are shown to have a better agreement with the Langmuir, although the difference in the extent of fit between the two models is not significant, particularly at the lower acid concentrations. The R^2 (0.95–0.99) for the Langmuir model and the χ^2 (0.12–0.45) are comparable with the R^2 values of 0.94–0.98 and χ^2 0.64–1.02 for the fitted Freundlich model. This would suggest that adsorption occurs by multilayer and monolayer adsorption. It is apparent that the fit of the Co-complexes adsorption to the Freundlich model is higher at the more acidic conditions. The dependence of the mechanism for cobalt adsorption to the Langmuir mechanism under acidic conditions also corresponds with the greater competition of the complexes with hydronium ions under this condition [24–26]. The stronger affinity of the resins towards the smaller cation (H^+) under acidic conditions would obviously reduce the crowding effects associated with the larger Co-complexes. This, as shown by the results in Table 3, promotes monolayer adsorption (see

Table 3
Adsorption isotherm parameters for cobalt organic complexes adsorbed onto Purolite S950

Acids	Concentration of acid (M)	Langmuir constants				Freundlich constants			
		Q_m (mg/g)	b (L/g)	R^2	χ^2	A (mg/g)	$1/n$	R^2	χ^2
Citric	0.01	5.39	3.9×10^{-1}	0.99	0.42	2.00	0.28	0.94	1.02
	0.1	7.31	5.1×10^{-2}	0.99	0.12	0.55	0.67	0.98	0.19
Malic	0.01	7.54	3.4×10^{-1}	0.95	0.45	2.08	0.39	0.96	0.72
	0.1	7.38	8.2×10^{-2}	0.99	0.18	0.81	0.54	0.98	0.23
Lactic	0.01	10.48	2.6×10^{-1}	0.99	0.39	2.81	0.35	0.97	0.90
	0.1	7.43	2.5×10^{-1}	0.99	0.40	2.14	0.34	0.97	0.64



Fig. 8. Monolayer adsorption of cobalt complexes as a result of site competition between hydrogen ions and metal complexes (Co-L: cobalt complex; H⁺: hydrogen ion).

Fig. 8). With increasing pH, Co-complexes were preferentially adsorbed. This appears to lead to steric hindrance that, as shown in Table 3, promoted multilayer adsorption. The overall outcome of these effects is the low Ni- and Co-organic acid complexes adsorption at the various pH.

4.3. Metal elution

The overall metal recovery also depends on the metal elution efficiency of the adsorbed metals. Elution efficiency was defined in this study, as the ratio of the mass desorbed from the resins to the mass adsorbed onto the resins. Table 4 compares the elution of nickel adsorbed on Purolite S950. The effects of variables including the nature of the complexes, metal (100–2000 mg/L) and acid concentrations (0.01 and 0.1 M) on metal elution were considered in this investigation. As shown, nickel complexes were easily eluted from the resins; elution efficiencies of about 90% were achieved. In general, similar elution efficiencies of nickel were achieved when adsorbed from various complexes and metal concentrations. Co-complexes were also found to be efficiently eluted from the resin (up to 98%) (see Table 5). It is clear, the nature of the ligand complexed to Co and Ni and metal concentrations have little effect on the cobalt desorption. This suggests the exchange reactions are equivalent for the three complexes considered in this study and that surface interaction between the resin and the metal complexes are independent of the metal speciation. Efficient elution of the metal complexes from the resin suggests the metal complexes interaction with the resin is based on weak bonds.

Table 4
Elution efficiency of nickel as a function of metal-complex concentrations

Acids	Elution from resins (%)		
	Concentration of Ni (ppm)	Concentration of acid	
		0.01 M	0.1 M
Citric	100	92	90
	500	92	89
	1000	92	89
	1500	92	89
	2000	93	90
Malic	100	91	91
	500	91	91
	1000	91	91
	1500	90	90
	2000	91	90
Lactic	100	91	91
	500	91	90
	1000	91	90
	1500	90	91
	2000	90	91

Table 5
Elution efficiency of cobalt as a function of metal-complex concentrations

Acids	Elution from resins (%)		
	Concentration of Co (ppm)	Concentration of acid	
		0.01 M	0.1 M
Citric	15	98	96
	50	98	82
	100	85	84
	200	88	86
Malic	15	94	91
	50	92	91
	100	92	95
	200	92	95
Lactic	15	94	98
	50	93	94
	100	93	92
	200	93	98

5. Conclusions

The equilibria of Ni- and Co-complexes adsorption onto Purolite S950 were investigated. Adsorption of Ni- and Co-complexed with citrate, malate and lactate ligands were generally low in comparison to metals complexed with sulfate or hydrated metals from aqueous solutions. This was attributed to the bulky organic ligands which promoted crowding effects or steric hindrance to adsorption sites. The relative adsorption capacities of the metals were found to be strongly dependent on the size of the ligands. Lactate which was the smallest ligand was found to have the highest adsorption capacity followed by the larger malate and citrate complexes. Adsorption of the bulky complexes, particularly under weakly acidic conditions where the resins exhibited higher metal adsorption, was predicted by the Freundlich models. This suggests metal uptake occurred by multilayer adsorption. The strong affinity of the resin for H⁺ under acidic conditions promoted competitive adsorption. This hampered the adsorption of the metal complexes and promoted monolayer adsorption. The relative stability of the metal-organic acid complexes meant ion-exchange of these complexes with Purolite S950 is almost impossible. This adsorption behaviour highlights the challenges in recovering Ni and Co from bioleaching solutions based on heterotrophic or fungi organism.

The elution efficiencies of both Ni- and Co-complexes from Purolite S950 resins were high (82–98%). It would appear the adsorption process involves weak interactions, where the nature of metal complexes and metal speciation has little effect on overall desorption efficiency from Purolite S950.

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