

# On The Fundamentals of Cr(III) Removal from Liquid Streams by a Bacterial Strain

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## ABSTRACT

This paper deals with the removal of Cr(III) species from liquid streams by a hydrophobic bacteria strain, *Rhodococcus opacus*. Zeta potential measurements, sorption and microflotation studies were carried out in order to evaluate the industrial potential application of such strain. It was observed that *R. opacus* exhibited an isoelectric point around pH 3.2 and the zeta potential profiles suffered a slight deviation after the contact with the sorbate. From the sorption studies, it was concluded that the highest metal removal took place at pH around 5.0 and the isotherm that best suited the sorption phenomenon was related to the Freundlich model with constants  $K_F = 1.71 \text{ mg}^{0.14} \cdot \text{dm}^{2.58} \cdot \text{g}^{-1}$  and  $1/n = 0.86$ . Furthermore, the kinetics data indicated that the biosorption yielded to 49.10 % of metal removal after 200 minutes; moreover, the pseudo-second order model fitted best the experimental data. Lastly, three different concentrations of *R. opacus* were tested in a bioflotation system. With only one cycle of operation, the highest biomass concentration,  $1.50 \text{ g} \cdot \text{dm}^{-3}$ , achieved 96.30 % of metal removal after 20 minutes of flotation.

**Keywords:** Biohydrometallurgy; Biosorption; Bioflotation; Liquid effluent; Chromium.

## 1. INTRODUCTION

Industrial activities yield considerable amount of residues which must be treated before its disposal in the environment via liquid, solid or gas effluents. Liquid effluents from various types of industries, such as metallurgy, electroplating, agro industry and others (Wang and Chen, 2006) are sources of heavy metals which can be hazardous for the flora and the fauna in the environment.

Due to the strict environmental regulations concerning the limits of concentration of pollutants in liquid effluents, conventional technologies have been improved and also new technologies have been tested to low down heavy metal concentration in aqueous media. Biosorption belongs to the second group of technologies and has yielded overriding results concerning heavy metal uptake from aqueous media. Biosorption can be defined as the uptake (removal) of metal and metalloid species, particulates or compounds by biological matter. It is free of biomass metabolism and may occur with dead or viable biomasses. On the other hand, metal uptake can be realized by means of metabolism activity and in this case it is termed bioaccumulation (Wase, Forster *et al.*, 1997). The discovery of biosorbents which exhibit favorable cost-efficiency relationship, when compared to conventional sorbents (activated carbon and ion exchange resins), has been proved to be a reality.

Many authors have dedicated their work for the exploitation of the metal uptake mechanisms by various types of biomasses, such as fungi (Akar and Tunali, 2006; Park *et al.*, 2005; Matis *et al.*, 2003a), bacteria (Selatnia *et al.*, 2004; Ramtek *et al.*, 2002), algae (Aksu and Dönmez, 2006; Pavasant and Apiratikul, 2006a; Aldrich and Feng, 2004), and other unusual biomasses and waste materials, such as coconut shells (Pino *et al.*, 2006), eggshells (Chojnacka, 2005), rice husk (Kumar and Bandyopadhyay, 2006), powdered waste sludge (Kargi and Pamukoglu, 2006) and many others. The majority of these works

aims only for bench scale batch sorption experiments. This fact should encourage the authors to emphasize their scientific quests with an engineering approach, that is, more experiments in pilot and industrial scale should have been executed, in order to use the obtained data in bench scale to design treatment processes of industrial liquid effluents.

Chromium(III) plays an important role in the metallurgical and chemical activities. On the other hand, it may pollute aqueous streams and therefore, arising several environmental problems. Although chromium(III) is an essential element, it can be toxic at elevated concentrations in the environment. It is reasonably known that the most stable valence state of chromium, in aqueous media, is the trivalent species and that in pH values between 4 and 10 the predominant species are  $\text{CrOH}^{2+}$ ,  $\text{Cr(OH)}_2^+$  and  $\text{Cr(OH)}_3.\text{aq}$ . If the total concentration of chromium(III) is higher than  $10^{-6}$  moles. $\text{dm}^{-3}$ , then polynuclear hydrolytic species products,  $\text{Cr}_2(\text{OH})_2^{4+}$ ,  $\text{Cr}_3(\text{OH})_4^{5+}$  and  $\text{Cr}_4(\text{OH})_6^{6+}$ , can also be expected. From Fig. 1, it can be observed that positive charged species predominate over a wide range of pH values for Cr(III) species. On the other hand, the speciation chemistry of Cr(VI), in aqueous solutions, contains only negative charged species, such as:  $\text{HCrO}_4^-$  (pH between 1 and 6) and  $\text{CrO}_4^{2-}$  (pH above 7). It is also known that Cr(VI) reduces to Cr(III) when the  $\text{H}^+$  concentration is increased and in more alkaline solutions (pH between 7 and 10) precipitation of  $\text{Cr(OH)}_3.\text{aq}$  becomes competitive with complexation (Stasicka and Kotaś, 2000).

In addition, one can realize that there are very few works in the literature on the use of *R. opacus* as a biosorbent for bio-hydrometallurgical or mineral processing applications (Mesquita *et al.*, 2003).

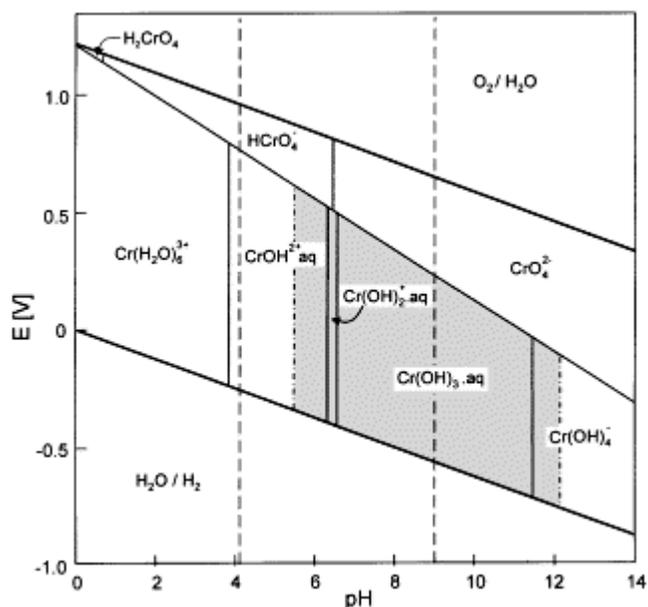


Fig. 1: Chromium species predomination diagram in diluted aerated aqueous solutions. The grey zone shows the domain of  $\text{Cr(OH)}_3.\text{aq}$  stability for  $10^{-6}$  moles. $\text{dm}^{-3}$  of total Cr.

(Stasicka and Kotaś, 2000)

The aim of this work was to study the ability of a *Rhodococcus opacus* strain to bind chromium metallic species from synthetic liquid effluents. The selected parameters and variables were: zeta potential, pH; most favorable bacteria concentration, metal concentration, pH and time influence on biosorption and bioflotation of the metal-laden bacteria using a Modified Hallimond tube.

## 2. MATERIALS AND METHODS

### 2.1 Biosorbent

The bacteria *R. opacus* was supplied by Fundação Tropical de Pesquisas e Tecnologia ANDRÉ TOSELLO – São Paulo, Brazil. It was acquired in the form of slants and was maintained in a refrigerator at 2.0 °C. This bacterial species is non-pathogenic

(Mesquita, 2000) and exhibits a significant hydrophobicity, due to its cell wall composition: palmitic acid, pentadecanoic acid, micolic acids and moieties of peptidoglycan (Klatte *et al.*, 1994).

The growth media (liquid) was composed by: yeast extract (3.0 g), malt extract (3.0 g), bacteriological peptone (5.0 g) and glucose (10.0 g) for 1.0 dm<sup>3</sup> of solution. The maintenance media (solid) was composed by: yeast extract (4.0 g), malt extract (10.0 g), glucose (4.0 g), CaCO<sub>3</sub> (2.0 g) and Agar (12.0 g) for 1.0 dm<sup>3</sup> of solution (before solidification). Stocks of bacterial biomass were made and renewed periodically using the maintenance media in Petri plates and saving them in a refrigerator at 2 °C. The bacterial solution was made by letting the bacteria grow for two days in a shaker (CIEN TEC CT-712) at temperature around 28 °C and 160 rpm. After the growing period, the bacterial solution was centrifuged and washed with distilled water three times. Lastly, it was saved in a solution of NaCl 0.01 moles.dm<sup>-3</sup> in the refrigerator (Mesquita, 2000).

## **2.2 Cr(III) Solutions and Chemical Analysis**

The source of aqueous Cr(III) was generated by the dissolution of chromium(III) sulfate, Cr<sub>4</sub>(SO<sub>4</sub>)<sub>5</sub>(OH)<sub>2</sub>, by VETEC, in distilled water. A stock solution of 1 g.dm<sup>-3</sup> chromium(III) was prepared. The analysis of the solutions, to determine chromium(III) concentration, was performed by the Perkin Elmer Atomic Absorption Spectrometer 1100B with reducing air-acetylene flame.

## **2.3 Biosorption Experiments**

Firstly, it was obtained the zeta potential curve for the bacterial species at 2.0 mg.dm<sup>-3</sup> concentration (Fig. 2) in the presence and in the absence of Cr(III) species,

using the Zeta-Meter System 3.0 apparatus. The temperature in all batch experiments was maintained around 28 °C. The contact time in all experiments was 24 h, except in the sorption kinetic and in the bioflotation studies.

The next step was to investigate the general studied biosorption parameters through batch experiments. The proper bacteria concentration was achieved by studying the effect of different bacteria concentrations (0.5, 1.0 and 1.5 g.dm<sup>-3</sup>) on the metal removal percentage (Fig. 3). The sorption capacity of *R. opacus*,  $q$  (mg of metal sorbed per gram of biosorbent), was calculated as shown above (Eq. 1):

$$q = \frac{V(C_i - C_{eq})}{M} \quad (\text{Eq. 1})$$

where  $V$  is the total volume of solution (dm<sup>3</sup>),  $C_i$  and  $C_{eq}$  are the initial and the equilibrium metal concentrations, respectively, (mg.dm<sup>-3</sup>) and  $M$  is the mass of biosorbent used (g).

After the most favorable bacteria concentration was chosen, the influence of the pH (2.0, 3.0, 4.0, 5.0 and 6.0) in the biosorption capacity of *R. opacus* was studied yielding to the results shown in Fig. 4.

Two sorption isotherms were studied, Langmuir (linearized, Fig. 5) and Freundlich (linearized, Fig. 6), with Cr(III) initial concentrations of 10, 20, 30, 60 and 90 mg.dm<sup>-3</sup>. Langmuir's model and its linearized form are expressed in Eq. 2.a and Eq. 2.b, respectively.

$$q = \frac{Q_m K_L C_{eq}}{1 + K_L C_{eq}} \quad (\text{Eq. 2.a})$$

$$\frac{C_{eq}}{q} = \frac{1}{Q_m K_L} + \frac{C_{eq}}{Q_m} \quad (\text{Eq. 2.b})$$

where  $Q_m$  is the biosorbent's maximum sorption capacity ( $\text{mg.g}^{-1}$ ),  $K_L$  is a constant related to the affinity between the biosorbent and the metal ( $\text{dm}^3.\text{mg}^{-1}$ ). This model is based on monolayer adsorption and each adsorption site has the same energy of adsorption as neighbor sites.

Freundlich's model and its linearized form are expressed in Eq. 3.a and Eq. 3.b, respectively.

$$q = K_F C_{eq}^{1/n} \quad (\text{Eq. 3.a})$$

$$\ln q = \ln K_F + \frac{1}{n} \ln C_{eq} \quad (\text{Eq. 3.b})$$

where  $K_F$  and  $1/n$  are constants related to the biosorbent capacity and biosorption intensity, respectively, ( $\text{mg}^{1-1/n}.\text{dm}^{3/n}.\text{g}^{-1}$  and no units, respectively). This model is empirical in nature and is based on multilayer adsorption.

Lastly, kinetic information of the biosorption was obtained by letting the bacteria solution in contact with  $10 \text{ mg}.\text{dm}^{-3}$  of metal solution for 5, 10, 15, 20, 25, 30, 40, 50, 100, 150 and 200 minutes. Two kinetic models were investigated. The pseudo-first order (Fig. 8) rate equation and its linearized form are represented in Eq. 4.a and Eq. 4.b, respectively. By using this model, it implies that the value of the metal uptake at equilibrium,  $q_{eq}$ , is already known, which is not always true. In order to compute the real  $q_{eq}$ , one should extrapolate the experimental data to  $t \rightarrow \infty$  or use a trial-and-error method (Aksu, 2001).

$$\frac{dq}{dt} = k_1 (q_{eq} - q) \quad (\text{Eq. 4.a})$$

$$\log (q_{eq} - q) = \log (q_{eq}) - \frac{k_1}{2,303} t \quad (\text{Eq. 4.b})$$

where  $q_{eq}$  is the amount of metal sorbed by amount of biosorbent at the equilibrium ( $\text{mg.g}^{-1}$ ),  $k_1$  is the velocity constant of the pseudo-first order model ( $\text{min}^{-1}$ ) and  $t$  is the contact time (min).

The pseudo-second order (Fig. 9) rate equation and its linearized form are represented in Eq. 5.a and Eq. 5.b, respectively. Both pseudo-first and pseudo-second order models are based on the sorption of a solid phase (the bacteria surface in this case), however the major difference between them is that the latter predicts the behavior over the whole range of sorption.

$$\frac{dq}{dt} = k_2 (q_{eq} - q)^2 \quad (\text{Eq. 5.a})$$

$$\frac{t}{q} = \frac{1}{k_2 q_{eq}^2} + \frac{1}{q_{eq}} t \quad (\text{Eq. 5.b})$$

where  $q_{eq}$  is the amount of metal sorbed by amount of biosorbent at the equilibrium ( $\text{mg.g}^{-1}$ ),  $k_2$  is the velocity constant of the pseudo-second order model ( $\text{g.mg}^{-1}.\text{min}^{-1}$ ) and  $t$  is the contact time (min).

All tests were done in duplicates and only one cycle of sorption was performed.

## 2.4 Bioflotation Experiments

Bioflotation experiments were accomplished with a Modified Hallimond tube. Bioflotation is based on the hydrophobicity of the bacteria and, therefore, their ability to adhere to air bubbles ascending in the tube and carrying the metal ions out of the solution. The air was pumped into the tube by the use of an air compressor vessel whose flow rate was previously calibrated.

Bacteria concentrations tested were 0.5, 1.0 and 1.5 g.dm<sup>-3</sup> and the flow rate used was 0.06 dm<sup>3</sup>.min<sup>-1</sup>. The contact times were 2, 5, 10, 20, 30, 40 and 50 minutes. Only one cycle of bioflotation was carried out in order to study the metal removal from the solution. The initial metal concentration was 10 mg.dm<sup>-3</sup>, pH values were maintained at 5.2 and temperature was 28 °C (Fig. 10). No surfactant was added due to the ability of the bacteria to generate foam.

### **3. RESULTS AND DISCUSSION**

#### **3.1 Zeta Potential Studies**

The zeta potential curve in Fig. 2 exhibits some useful information for the upcoming experiments. It can be noticed that the isoelectric point (IEP) of *R. opacus* was 3.2, which is in accordance with the results obtained by Mesquita (2000). Before the IEP, the bacteria surface is positively charged and after the IEP it is negatively charged, which is favorable for Cr(III) species uptake, considering a predominant electrostatic adsorption. After the biosorption, it was noticed a slight deviation of the zeta potential curve against pH, which can be attributed to the occupation of the bacteria active sites by the Cr(III) species, thus lowering the absolute values of zeta potential.

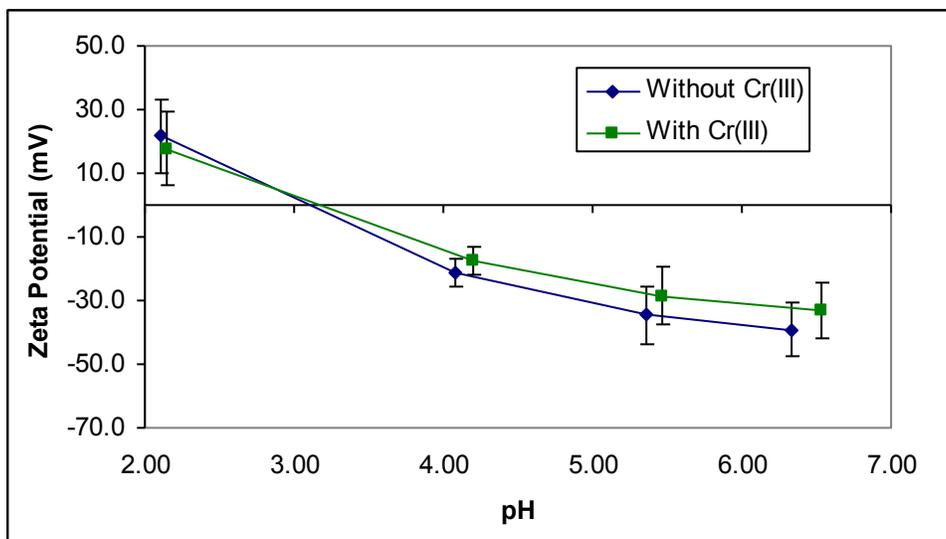


Fig. 2: Zeta potential curve for *R. opacus* at concentration of  $2.0 \text{ mg.dm}^{-3}$  before and after Cr(III) biosorption. The initial Cr(III) concentration was  $10 \text{ mg.dm}^{-3}$  and the indifferent electrolyte was NaCl at the concentration of  $0.01 \text{ moles.dm}^{-3}$

### 3.2 Chromium(III) Biosorption Evaluation

#### 3.2.1 Bacteria Concentration Study

Fig. 3 shows the results achieved for different bacteria concentrations. It can be concluded that the metal species removal percentage was not deeply influenced by this kind of parameter. Therefore, the chosen bacteria concentration for all the subsequent tests was  $0.5 \text{ g.dm}^{-3}$ , which presented the highest metal sorption capacity,  $q$ .

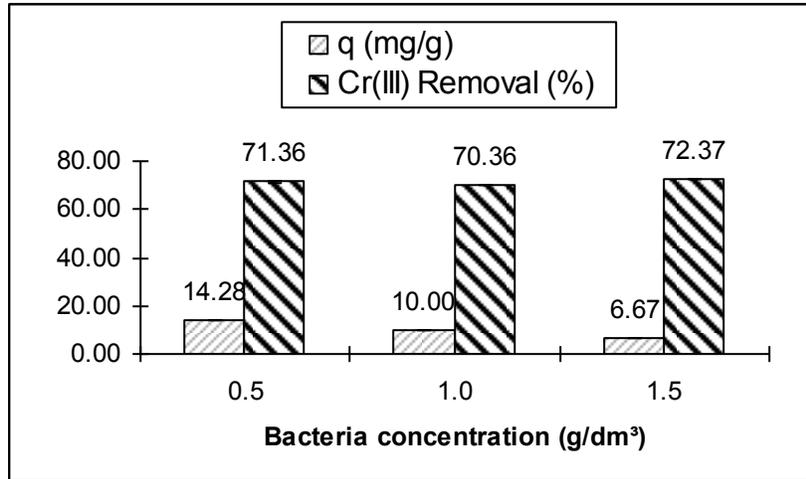


Fig. 3: Most favorable bacteria concentration test results. The initial Cr(III) concentration was  $10 \text{ mg} \cdot \text{dm}^{-3}$  and the pH was maintained at 5.2.

### 3.2.2 Influence of pH

The biosorption showed to be very sensitive to pH (Fig. 4) values as it would be expected after analyzing the zeta potential curve. The highest metal removal percentage took place in pH around 5.0, as the bacteria presented the most negative zeta potential before the precipitation of  $\text{Cr}(\text{OH})_3$  began to occur (above pH 7.0). At lower pH values, the biosorption was very poor, which suggests that a weak attraction between the bacteria surface and the metal species took place, however a clearer understanding of the mechanisms involved in the biosorption could be achieved by means of analysis of SEM (Scanning Electronic Micrography), TEM (Transmission Electronic Micrography) and IR (infrared) spectra. For instance, Pan *et al.* (2006) used IR analysis to determine which functional groups of the *Bacillus cereus* biomass are responsible for Pb(II) biosorption; their conclusions state that the functional groups may include carboxyl, hydroxyl and amino groups.

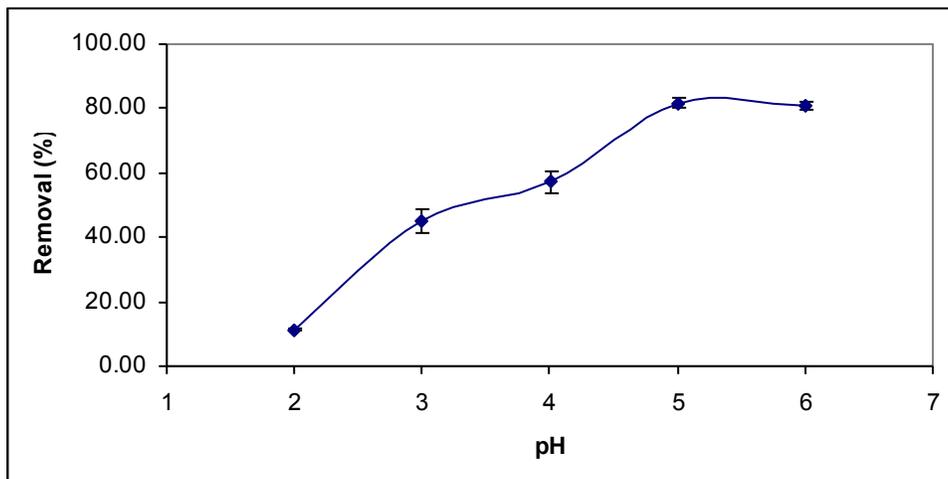


Fig. 4: Influence of pH on biosorption of Cr(III) species.

The initial Cr(III) concentration was  $10 \text{ mg.dm}^{-3}$ .

In comparison with other results found in the literature, Akar and Tunali (2006) studied the biosorption of Pb(II) and Cu(II) using *Aspergillus flavus* biomass. The sorbates initial concentrations were higher ( $100 \text{ mg.dm}^{-3}$  and  $50 \text{ mg.dm}^{-3}$ , respectively) than the one used in this work for Cr(III). For Cu(II), the authors obtained around 96.8 % of metal removal and pH around 2.0 and around 93.6 % of metal removal at pH around 5.0. Pavasant *et al.* (2006b) studied the biosorption of Cu(II), Cd(II), Pb(II) and Zn(II) using *Caulerpa lentillifera* macroalga. For Cd(II), at the same concentration as the one used in this work for Cr(III), around 35 % of metal removal were achieved around pH 4.0 and around 75 % of metal removal were accomplished around pH 6.0. Hence, the results obtained in this work are in good agreement when compared to those found in articles with similar methodology.

### 3.2.3 Sorption Isotherms Studies

Fig. 5 and Fig. 6 show the results regarding the sorption isotherms. Table 1 shows the values of the constants of each model. It is clear that the Freundlich fits better the *R. opacus* biosorption of Cr(III), hence the biosorption is a multilayered process.

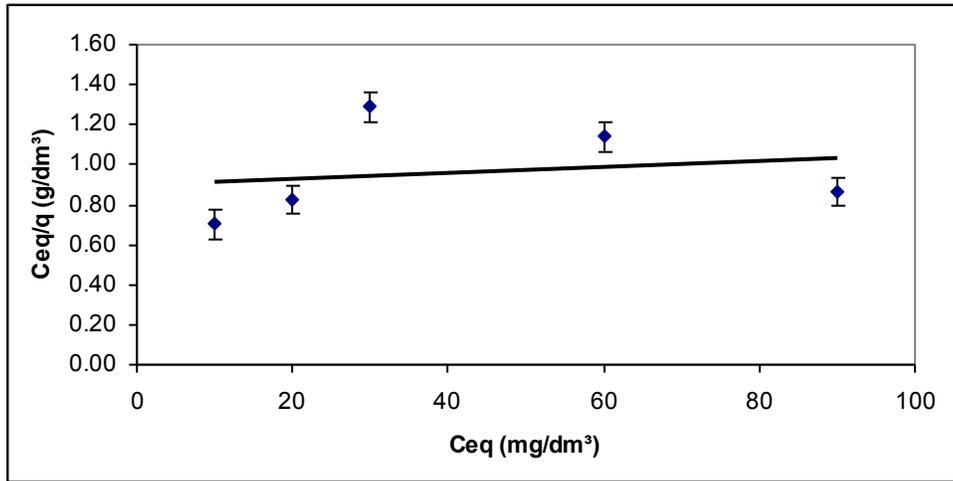


Fig. 5: Langmuir model: linearized form

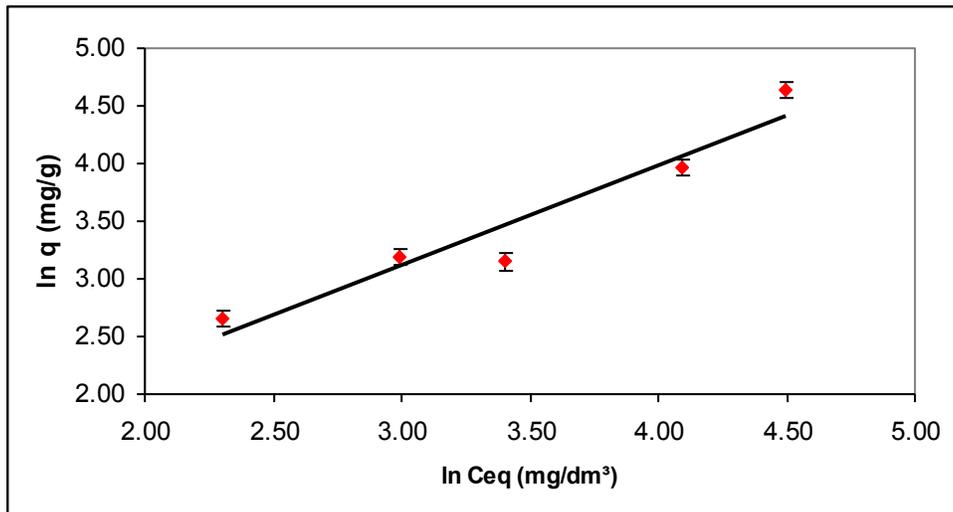


Fig. 6: Freundlich model: linearized form

Model	Parameters
Langmuir	$Q_m = 714.29 \text{ mg.g}^{-1}$ $K_L = 1.50 \times 10^{-3} \text{ dm}^3.\text{mg}^{-1}$ $R^2 = 0.037$
Freundlich	$K_F = 1.71 \text{ mg}^{0.14}.\text{dm}^{2.58}.\text{g}^{-1}$ $1/n = 0.86$ $R^2 = 0.923$

Loukidou *et al.* (2005) studied the biosorption of Cd(II) using *Aeromonas caviae* bacteria strains. The heavy metal concentration varied from 5 to 350 mg.dm<sup>-3</sup>. For a concentration of 0.5 g.dm<sup>-3</sup> of biomass and at 20 °C, the Freundlich parameters,  $K_F$  and  $1/n$ , obtained were 0.020 mg<sup>0.61</sup>.dm<sup>1.16</sup>.g<sup>-1</sup> and 0.39 ( $R^2 = 0.87$ ), respectively, on the other hand the Langmuir parameters,  $Q_m$  and  $K_L$ , obtained were 181.91 mg.g<sup>-1</sup> and 0.03 dm<sup>-3</sup>.mg<sup>-1</sup> ( $R^2 = 0.93$ ), respectively. Singh *et al.* (2005) studied a variety of low-cost activated carbons for biosorption of hexavalent chromium. The authors observed that the Freundlich parameters (at 25 °C),  $K_F$  and  $1/n$ , for a commercially available activated carbon cloth fabric (ACF) were 0.1950 mg<sup>0.19</sup>.dm<sup>2.43</sup>.g<sup>-1</sup> and 0.8091 ( $R^2 = 0.9522$ ), respectively. Thus, the results presented in this work match the level of those encountered in the literature for different kinds of biosorbents undergone a comparable methodology.

### 3.2.4 Kinetic Studies

The sorption kinetics of chromium(III) by *R. opacus* has not shown to be very fast, in comparison with other metals (Vásquez, 2006). Within 200 minutes, nearly 50 % of the initial metal concentration (10 mg.dm<sup>-3</sup>) was removed. Fig. 7 shows the metal removal percentage as a function of contact time. It can be verified that the equilibrium had not been achieved yet within 200 minutes. The experimental parameters are shown in Table 2.

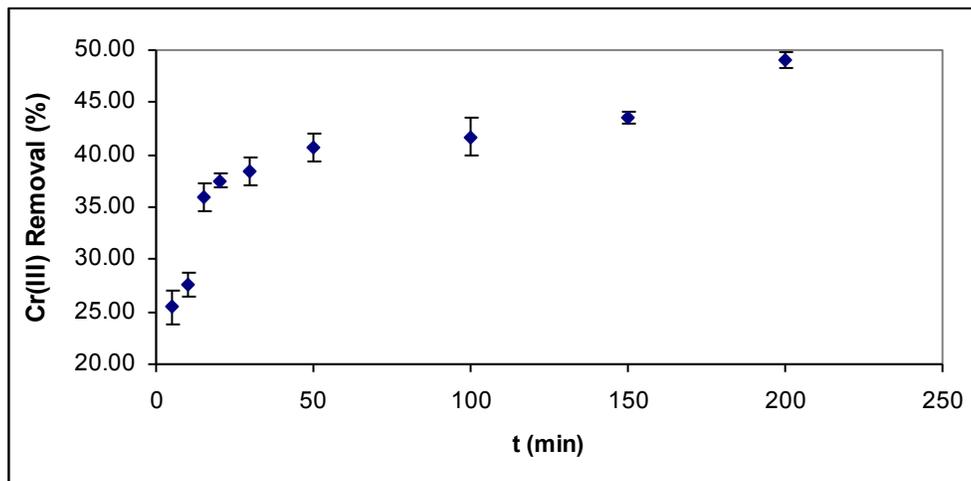


Fig. 7: Kinetic data: metal removal percentage as a function of time.

Parab *et al.* (2006) evaluated the biosorption of Co(II), Cr(III) and Ni(II) onto coir pith. The kinetic studies showed that the equilibrium of Cr(III) biosorption was achieved after 80 minutes of contact with the metal solution and yielded around 60 % of metal removal. The initial metal concentration was higher ( $50 \text{ mg.dm}^{-3}$ ) than the one used in this work.

In this work, two kinetic models have been studied. The pseudo-first order did not fit well the experimental data obtained; by using this model, as discussed in section 2.3, the value of  $q_{eq}$  used to plot Fig. 8 was the mean value between the metal uptake in the most favorable bacteria concentration and sorption isotherms experiments, yielding to  $14.265 \text{ mg.g}^{-1}$ . The constant was calculated by the slope of the curve.

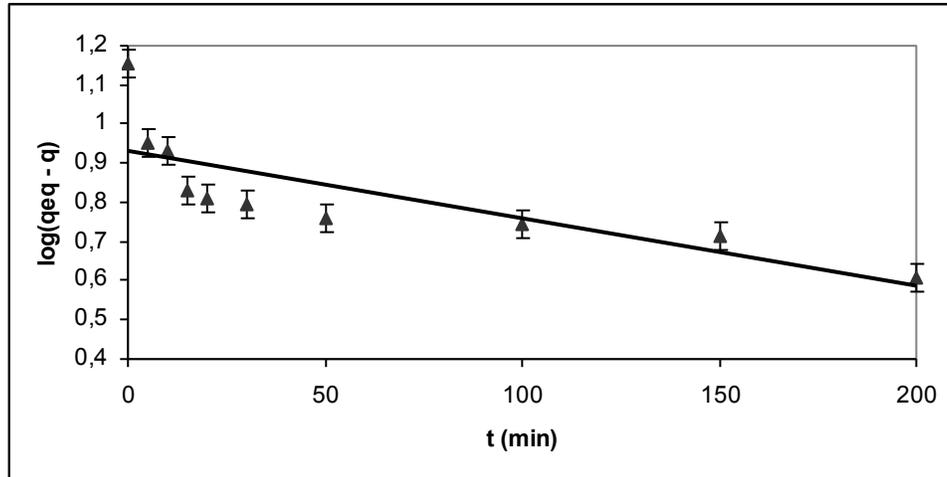


Fig. 8: Pseudo-first order model: experimental data

The pseudo-second order fitted well the experimental data and is shown in Fig. 9. The experimental  $q_{eq}$  value deviated 2.93 % from the theoretical value, calculated by the slope of the curve.

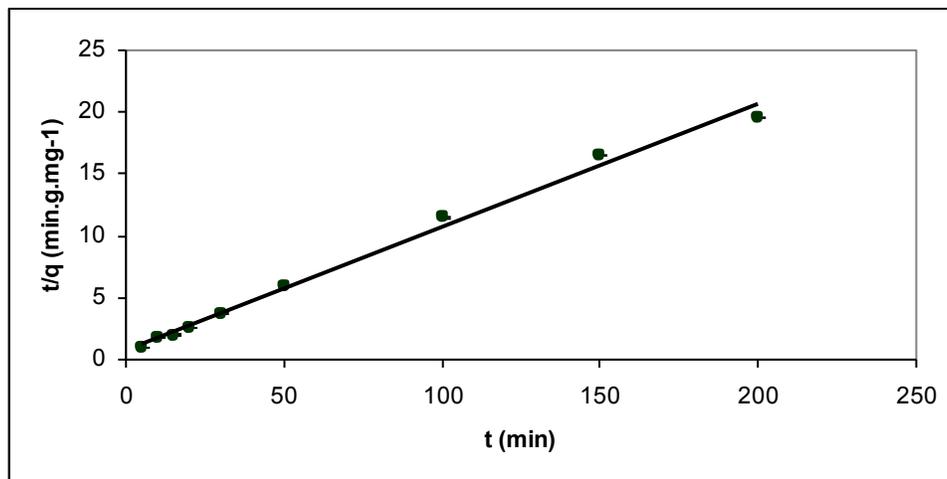


Fig. 9: Pseudo-second order model: experimental data

Table 2: Kinetic parameters of the Pseudo-first and Pseudo-second order models

Pseudo-first order	$q_{eq} = 8.50 \text{ mg.g}^{-1}$	$k_1 = 3.90 \times 10^{-3} \text{ min}^{-1}$
	$R^2 = 0.612$	
Pseudo-second order	$q_{eq} = 10.09 \text{ mg.g}^{-1}$	$k_2 = 1.28 \times 10^{-2} \text{ g.mg}^{-1}.\text{min}^{-1}$
	$R^2 = 0.993$	

These results are in accordance with those found in the literature for a similar methodology applied. For instance, Parab *et al.* (2006) observed that the pseudo-second order model fitted best the biosorption of Cr(III) onto coir pith. For an initial metal concentration of  $20 \text{ mg.dm}^{-3}$ , the amount of metal sorbed at equilibrium and velocity constant,  $q_{eq}$  and  $k_2$ , were  $9.82 \text{ mg.g}^{-1}$  and  $0.0091 \text{ g.mg}^{-1}.\text{min}^{-1}$ , respectively. Aksu (2001) studied the biosorption kinetics of Cd(II) into the green alga *Chlorella vulgaris*. The author concluded that the pseudo-second order model fitted best the biosorption due to the best correlation of data ( $R^2 = 0.999$ ); for a initial concentration of  $100 \text{ mg.dm}^{-3}$  (at  $20 \text{ }^\circ\text{C}$ ) and  $0.75 \text{ g.dm}^{-3}$  of biomass, the observed amount of metal sorbed at equilibrium and velocity constant,  $q_{eq}$  and  $k_2$ , were  $62.3 \text{ mg.g}^{-1}$  and  $0.00341 \text{ g.mg}^{-1}.\text{min}^{-1}$ , respectively.

### 3.6 Bioflotation Study

Metal-laden *R. opacus* showed great ability to float out of the solution in the Modified Hallimond tube system as can be inferred from Fig. 10. The biomass concentration which showed the best results was the highest one adopted,  $1.5 \text{ g.dm}^{-3}$ , which produced a considerable amount of foam that floated the metal-laden bacteria out of the system. The metal removal reached a value of 96.30 %.

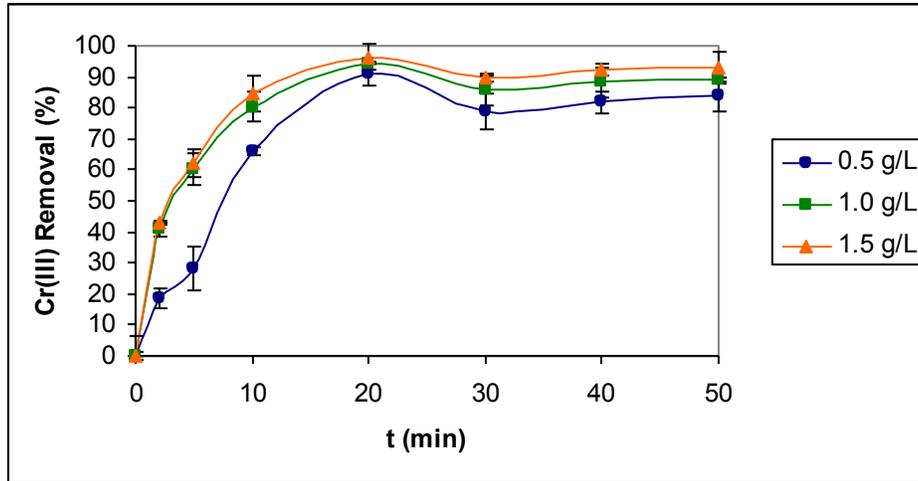


Fig. 10: Bioflotation results. Initial Cr(III) concentration was  $10 \text{ mg} \cdot \text{dm}^{-3}$  and the flow rate used was  $0.06 \text{ dm}^3 \cdot \text{min}^{-1}$

The recent literature shows that microorganisms have yielded an outstanding performance in bioflotation systems for different heavy metals removal.

Vásquez (2005) studied the bioflotation of *R. opacus* in a solution of Cd(II). The dispersed air flotation system was composed by a column with inner diameter of 5.7 cm and height of 95 cm (volumetric capacity:  $1.3 \text{ dm}^3$ ), an air compressor and an air sparging glass plate at the bottom of the column. The author obtained good results with that system with only one cycle: 93 % of metal removal. Matis *et al.* (2003b) studied another bioflotation system (dispersed-air flotation, DAF). Three biosorbents were studied: a fungal biomass (*Penicillium chrysogenum*, with trade name Mycan), an actinomyces bacterium (*Streptomyces rimosus*) and yeast (*Saccharomyces carlsbergensis*). The DAF column had a retention time of 600 s and superficial air velocity of  $0.27 \text{ cm} \cdot \text{s}^{-1}$ . Dodecylamine was added as a collector. Among other variables the authors have studied, they observed that an increase in the *S. rimosus* concentration and in the flow rate improved the removal of

copper (around 100 % at 1.25 g.dm<sup>-3</sup> of biomass), zinc (around 40 % at 2.0 g.dm<sup>-3</sup> of biomass) and nickel (around 20 % at 2.0 g.dm<sup>-3</sup> of biomass). The authors also executed multiple cycles in which flotation collector was supplied in the first and in the third cycles. It was noticed that the absence of dodecylamine in one cycle yielded a slight decrease of flotation. Copper removal in multiple cycles was around 100 %, zinc removal was around 25 % and nickel removal was around 15 %. Those results are in good accordance to the data obtained in the present work.

#### 4. CONCLUSION

*R. opacus* exhibited positively charged surface below pH 3.2 and negatively charged surface above this value. This explains its highest efficiency in the metal removal (81.76 %) at pH 5.0. The zeta potentials did not change considerably after Cr(III) biosorption. The most favorable bacteria concentration was 0.5 g.dm<sup>-3</sup> which exhibited 71.36 % of metal removal (14.28 mg of metal sorbed per g of bacteria) in only one cycle of sorption.

The isotherm sorption that fitted best the biosorption data was Freundlich model ( $R^2 = 0.923$ ). Regarding the sorption kinetics, *R. opacus* was capable of 49.10 % of metal removal in 200 minutes. The pseudo-second order model fitted best the biosorption data ( $R^2 = 0.993$ ).

Lastly, the bioflotation system investigated showed to be efficient for floating metal-laden *R. opacus* because in only one cycle of experiment, the maximum metal removal was 96.30 % in 20 minutes of flotation by a biomass concentration of 1.5 g.dm<sup>-3</sup>. Other systems may be investigated in order to exploit the use of these bacteria in liquid effluents treatment technology.

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