Single and binary component sorption of the fission products Sr^{2+}, Cs$^+$ and Co^{2+} from aqueous solutions by sulphate reducing bacteria

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Abstract

This study investigates the removal of the fission products Sr^{2+}, Cs$^+$ and Co^{2+} in single and binary metal solutions by a sulphate reducing bacteria (SRB) biomass. The effect of initial concentration and pH on the sorption kinetics of each metal was evaluated in single metal solutions. Binary component equilibrium sorption studies were performed to investigate the competitive binding behaviour of each metal in the presence of a secondary metal ion. Results obtained from single metal equilibrium sorption studies indicated that SRB have a higher binding capacity for Sr^{2+} (q_{max} = 416.7 mg g^{-1}), followed by Cs$^+$ (q_{max} = 238.1 mg g^{-1}), and lastly Co^{2+} (q_{max} = 204.1 mg g^{-1}). Among the binary systems investigated, Co^{2+} uptake was the most sensitive, resulting in a 76% reduction of the sorption capacity (q_{max}) in the presence of Cs$^+$. These findings are significant for future development of effective biological processes for radioactive waste management under realistic conditions.

KEYWORDS: reaction kinetics, bacteria, waste processing, mineral processing, environmental.

1. INTRODUCTION

Hazardous metals and radionuclides are released into the environment through contaminated wastes frequently produced from several industries, including mining, metallurgical, electronic, electroplating, metal finishing and during the burn up of nuclear fuel in a nuclear reactor (Zouboulis et al., 2004; Lloyd and Renshaw, 2005). The presence of radionuclides and their fission products, even at low concentrations, in various industrial wastes is of more concern, as they pose serious chemical and radiological toxicity threats to lower and higher living organisms. Among these, the radioactive isotope of strontium (Sr-90) is of great concern and its toxic effects on human beings are well documented (Chen, 1997; Kossman and Weiss, 2000; Noshchenko, 2002; Greve et al., 2007). Commonly, proposed methods, used for removal of Sr-90 and Cs-137 are adsorption on zeolite, clay mineral, and synthetic organic ion exchangers. However, the main disadvantages with the above methods is their unsuitability at high pH, high sodium concentrations, and in irradiated environments (Chaalal and Islam, 2001).

For this reason, emphasis is now given to the utilization of microbial adsorbents for the removal and recovery of heavy metal contaminants since they have been shown to possess high capacities for the selective uptake of metals from dilute metal-bearing solutions (Beveridge, 1989; Mullen et al., 1989; Chubar et al., 2008). The adsorption of large quantities of metal ions onto bacterial surfaces has been the main focus for the development of effective metal bioremediation strategies. Bacteria have a variety of different surface formats for their cell walls. At neutral pH, almost all of these surfaces have an overall electronegative charge due to the presence of a variety of surface organic functional groups,

such as amino, carboxylic, hydroxyl, and phosphate sites. Bacteria, being microscopic and having highly reactive cell surfaces (interfaces), are considered to be exquisitely efficient environmental catalysts for metal ion adsorption and mineral nucleation (Douglas and Beveridge, 1998). The use of sulphate reducing bacteria (SRB) for metal remediation is not a new concept; however their recent occurrence in radioactive environments (Chicote et al., 2004) has revived the interest in their application for radioactive waste remediation. In this study, Sr^{2+}, Cs^+ and Co^{2+} removal from single and binary metal systems by a sulphate reducing bacteria consortium was investigated.

2. MATERIALS AND METHODS

2.1 Reagents and apparatus

All chemicals used were of analytical grade, and were purchased from Merck (South Africa), unless stated otherwise. All glassware was soaked in 10% HNO_3 and rinsed with distilled water prior to and after use to remove any traces of metal ions. Metal stock solutions for Sr^{2+}, Cs^+ and Co^{2+} were prepared from $SrCl_2.6H_2O$, $CsCl$ and $Co(NO_3)_2.6H_2O$, respectively, by dissolving the appropriate amount in 10mL HNO_3/distilled water solution (1:1) and then diluted to 1 L to give a final concentration of 1000 µg mL^{-1}. Working concentrations and standard solutions were prepared by diluting the stock solution with distilled water to give the desired concentration.

2.2 SRB Growth and Preparation

A SRB starter culture, previously isolated from a mine dumpsite, was kindly supplied by Dr Harma Greben (CSIR, South Africa). The microorganisms were grown anaerobically in

sterile modified Postgate medium C containing (L^{-1}); 6 mL sodium lactate (60% solution w/v), 1.0 g yeast extract, 1.0 g NH_4Cl, 4.5 g Na_2SO_4, 0.5 g KH_2PO_4, 0.06 g $MgSO_4.7H_2O$, 0.1 g sodium citrate.$2H_2O$, 0.06 g $CaCl_2.6H_2O$, 0.1 g ascorbic acid and 0.1 g sodium thioglycollate, prepared according to published procedures (Postgate, 1984). The suspension was incubated at 30 ±3ºC in the dark with continuous stirring at 120 rpm. For sorption experiments, SRB cells were harvested during mid-stationary growth phase (day 5-6) by centrifugation at 3300×g, for 15 minutes. The cells were repeatedly washed first in distilled water then in a saline solution (0.1 M NaCl) to remove residual sulphide as well as other impurities. SRB biomass density was expressed as dry weight (g). This was measured after drying the cells in an oven at 80ºC for 48 hours.

2.3   Kinetic experiments for metal sorption

Kinetic sorption experiments for the effect of initial concentration and pH on the removal of Sr^{2+}, Cs^+ and Co^{2+} from single metal solutions were performed in 100 mL rubber-sealed serum bottles. The initial metal concentration and pH was varied between 25-500 mg L^{-1} and 2-9, respectively, while SRB cell density was kept constant at 0.5 g L^{-1}. Samples (1mL) were removed at timed intervals by sterile syringes for residual metal analysis. Metal concentration was determined by an AAnalyst400 Perkin Elmer AAS (Perkin Elmer, Shelton, USA). The metal uptake capacity (q_{eq}) was calculated as:

$$q_{eq} = \frac{\left(C_i - C_{eq}\right)}{x}$$

(1)

where: q_{eq} = metal uptake capacity (mg g^{-1}), C_i = initial concentration of metal in solution (mg L^{-1}), C_{eq} = equilibrium concentration of metal in solution (mg L^{-1}) and x = dry weight of SRB added (g).

2.4   Equilibrium studies for metal sorption

The equilibrium removal of Sr^{2+}, Cs$^+$ and Co^{2+} from single and binary metal solutions was evaluated. The initial concentration was varied between 25 and 1200 mgL^{-1} for single metal isotherms. The competitive removal of metal ions from binary metal solutions was carried out by adding equivalent initial concentrations of the target and competing metal ion ranging from 25 to 1200 mg L^{-1}. In all experiments, pH and SRB cell density was kept constant at 4 and 0.5 g L^{-1}, respectively. Samples (1mL) were removed by sterile syringes at equilibrium for residual metal analysis. Metal concentration was determined by an AAnalyst400 Perkin Elmer AAS.

2.5   Kinetic data modelling

Adsorbent capacity based on first and second-order reaction rate kinetic models were used in the present study to describe the mechanism of the uptake of Sr^{2+}, Cs$^+$ and Co^{2+} by SRB cells, and identify the main factors controlling sorption rate. The pseudo-first-order (Eq. 2) and -second-order (Eq. 3) kinetic models can be represented as (Lagergren, 1898):

$$\frac{\mathrm{d}q_t}{\mathrm{d}t} = k_1\left(q_{eq} - q_t\right) \tag{2}$$

$$\frac{\mathrm{d}q_t}{\mathrm{d}t} = k_2\left(q_{eq} - q_t\right)^2 \tag{3}$$

where: q_t = concentration of ion species in the sorbent at time t (mg g^{-1}), q_{eq} = equilibrium concentration of adsorbed ionic species in the sorbent (mg g^{-1}), k_1= biosorption constant of pseudo-first-order Lagergren equation (min^{-1}) and k_2= biosorption constant of pseudo-second-order Lagergren equation (min^{-1} g mg^{-1}).

After integration by applying boundary conditions ($q_t = 0$ at $t = 0$ and $q_t = q_t$ at $t = t$), the Lagergren pseudo-first-order (Eq. 2) and pseudo-second-order (Eq. 3) models can be rearranged for linearized data plotting as follows (McKay and Ho, 1999):

$$log\left(q_{eq} - q_t\right) = log\left(q_{eq}\right) - \frac{k_1}{2.303}t \tag{4}$$

$$\frac{t}{q_t} = \frac{1}{k_2 q_{eq}^2} + \frac{1}{q_{eq}}t \tag{5}$$

The applicability of each model for describing the sorption process is determined from parameters obtained from a linear relationship of log (q_{eq}–q_t) versus t, and t/q_t versus t for the pseudo-first-order and –second-order kinetic models, respectively. In a true pseudo-first-order kinetic process, experimental log q_{eq} should be equal to the intercept of the straight line of a plot of log (q_{eq}–q_t) versus t. The Lagergren pseudo-first-order kinetic equation is most suited for experimental data where metal ion uptake capacity steadily increases for the whole range of the contact time. However, in most cases sorption tends to be uniform and rapid for the first 20 to 30 minutes of contact, followed by a slower phase whereby metal uptake is significantly decreased. As the sorption process progresses through the latter phase, the amount of metal ion sorbed becomes significantly lower than the equilibrium amount (Ho and McKay, 1998).

On the other hand, the pseudo-second-order model predicts sorption over the whole range of contact time, and is in agreement with a mechanism where chemisorption processes, such as adsorption are the rate-controlling steps (Aksu, 2001). The close match between the experimental and model q_{eq} values obtained from the linear plot of t/q_t versus t confirms the applicability of the pseudo-second-order model (McKay and Ho, 1999).

2.6   Equilibrium data modelling

Classical sorption models, the Langmuir isotherm and Freundlich isotherms were used to evaluate the removal of Sr^{2+}, Cs^+ and Co^{2+} in single and binary metal solutions. The Langmuir isotherm model is represented by the equation:

$$q = \frac{q_{max}\, bC_{eq}}{1 + bC_{eq}}$$ (6)

and the Freundlich isotherm model by:

$$q = kC_{eq}^{(1/n)}$$ (7)

where: q = sorption uptake (mg g^{-1}), q_{max} = maximum sorbate uptake (mg g^{-1}), b = coefficient related to the affinity between the sorbent and sorbate, C_{eq} = equilibrium concentration of the sorbate remaining in the solution (mg L^{-1}), k = constant corresponding to the binding capacity and n = coefficient related to the affinity between the sorbent and sorbate.

3. RESULTS AND DISCUSSION

3.1 Effect of concentration on the kinetics of Sr^{2+}, Cs^+ and Co^{2+} removal

In most cases of sorption processes the initial metal concentration serves as an important driving force for the mass transfer of metal ions onto sorbents, such that higher initial metal concentrations result in increased metal uptake (Aksu, 2001). Similarly, in the present study, the SRB culture exhibited an increased metal removal capacity with increasing initial concentration. In the present study, the uptake of the divalent cations; Sr^{2+} (Figure 1) and Co^{2+} (Figure 2) exhibited the same uptake trend, whereby the uptake increased with increasing initial concentration. However, Cs^+ sorption by SRB increased until a maximum uptake capacity of 118 mg g^{-1}, after which uptake decreased (Figure 3). Generally, the uptake of metals by SRB was observed in the order Cs<Co<Sr.

The pseudo-first-order model did not fit well to all the data obtained for the whole range of the contact time; hence lower correlation coefficients were obtained (data not shown). Such observations have been reported for the sorption of a range of metals from aqueous solution by biomass, suggesting that it is a common feature for most sorption systems. The main limitation with the first-order equation of Lagergren is that it is generally applicable for the initial rapid uptake which lasts for about 20–30 minutes of the sorption process (Ho and McKay, 1998). The best fit for the data obtained on the effect of initial concentration on Sr^{2+}, Cs^+, and Co^{2+} removal was achieved with the pseudo-second-order kinetic model with the parameters obtained for each metal as shown in Table 1. Generally, there was a decrease in rate constant with increasing initial concentration and removal capacity for the divalent cations (Sr^{2+} and Co^{2+}), as a result of the higher removal efficiencies at lower

solute concentrations. In summary, the obtained results suggest that the present metal removal process is not a first-order reaction. Based on the observation that the best fit was achieved with the pseudo-second-order kinetic model, it can be assumed that the rate limiting step of the metal removal process may be due to chemisorption processes.

3.2 Effect of pH on the kinetics of Sr^{2+}, Cs^+ and Co^{2+} removal by SRB

Solution pH is another important factor in the removal of metals from aqueous solutions, as it affects the surface charge of the adsorbent, the degree of the ionization and the speciation of the adsorbate (Choudhary and Sar, 2009). Speciation studies for Sr^{2+}, Cs^+ and Co^{2+} at pH 2-9 was determined by the chemical speciation model MINTEQ (Allison et al 1990). At an initial concentration of 75 mg L^{-1} and pH range 2-9, results obtained revealed that the bulk of both Sr (99.8%) and Cs (99.96%) species in solution occurred in the highly dissociated form, while only about 0.2% existed as $SrCl^+$ and about 0.04% CsCl. This observation strongly suggests that both cations undergo limited hydrolysis, which is in agreement with earlier findings by Baes and Mesmer (1976).

With regard to Co^{2+} speciation, both initial concentration and pH played a significant role in determining the dominant Co^{2+} species in solution. Generally, an increase in pH resulted in the decrease of highly dissociated Co species. At low pH (pH 2-4), Co species distribution was as follows: 99.7% Co^{2+} and 0.3% $CoNO_3^+$. At near neutral pH (pH 5-7) slight precipitation occurred as Co species were distributed as follows: 99.68% Co^{2+}, 0.3% $CoNO_3^+$ and 0.016% $CoOH^+$. Increasing the pH to 8 resulted in eminent Co^{2+} precipitation due to the formation of about 0.12% $Co(OH)_2$, while the of the Co species were distributed

as follows: ~97% Co^{2+} and 2% $CoOH^+$. Further increasing the pH to 9, resulted in increased precipitation where about 10% of the concentration existed as $Co(OH)_2$, while about 77% existed as Co^{2+}, 0.3% as $CoNO_3^+$, 13% $CoOH^+$ and 0.1% $Co_4(OH)_4^{4+}$. These findings are also in agreement with earlier studies on Co^{2+} hydrolysis reported in literature (Baes and Mesmer, 1976).

In this study, Sr^{2+} sorption by SRB was pH independent as there was minimal differences in the uptake capacities at different pH ranges (Figure 4). In view of the speciation data obtained, equal free metal ion availability resulted in an almost similar removal capacity at the different pH values. The present SRB culture has demonstrated a unique high Sr^{2+} binding, as neither binding site deprotonation nor protonation due to changes in pH affected uptake as previously hypothesized in other studies. Cs^+ removal, on the other hand was dependent on the solution pH (Figure 5). High Cs^+ removal was observed between pH 2 and 6, thereafter an increase in pH resulted in decreased uptake. This is a common feature where sorption is pH dependent as functional groups with low pKa values such as a carboxyl (pKa 3.0–4.0) and other side chain carboxyl groups (pKa 4.0–4.5) undergo deprotonation as a function of increasing pH, resulting in a net negative charge bacterial above a pH of approximately 2.0, thus favoring metal binding (Fein et al., 1997; Douglas and Beveridge, 1998). Similarly, the pH dependent uptake of Cs^+ can be attributed to the deprotonation of cell wall functional groups that occurs with increasing pH, progressively resulting in increased Cs^+ uptake capacity until all the binding sites are saturated.

Solution pH played an important role in determining the removal mechanism and consequently the sorption capacity of Co^{2+} from solution (Figure 6). Results from speciation analysis at the different pH values revealed that Co^{2+} availability decreases at pH > 7 due to precipitation. Therefore, the observed steady increase in Co^{2+} uptake with increasing pH may be attributed to other non-specific metal binding mechanisms including chemical precipitation due to the formation of insoluble Co(II) hydroxide species. For this reason future studies on Co will be conducted at pH <6 so as to avoid premature precipitation of the metal species.

The pseudo-second-order kinetic model provided the best fit for the data obtained on the effect of pH on the removal of Sr^{2+}, Cs^+, and Co^{2+} from single metal systems by SRB. The model parameters obtained for each metal species at pH 2-9 are shown in Table 2. All the correlation coefficients obtained were ≥0.996, which indicated the suitability of this model. Higher removal capacity was coupled to lower rate constants for Sr^{2+}. Similarly, the fit of the data to the pseudo-second-order model is in agreement with a mechanism where adsorption is the main rate controlling step.

3.3 Single metal isotherms

Equilibrium sorption isotherms provide basic information on a given system and are useful for comparing different biosorbents and affinities of different metal ions for the same biosorbent (Gadd, 2009). In this study, the data was analysed with the linearized Langmuir (Eq. 6) and Freundlich isotherm models (Eq. 7). Model parameters for the Langmuir isotherm were determined from a linear plot of $1/q$ vs. $1/C_{eq}$; q_{max} and b were estimated

from the intercept and slope, respectively. The Freundlich isotherm model was linearized by plotting log q vs. log C_{eq}. The constants k and n were estimated from the intercept and slope, respectively.

The Langmuir isotherm model provided the best fit for the equilibrium data for Sr^{2+}, Cs^+, and Co^{2+} removal from single metal systems by SRB (Figure 7). Low correlation coefficients were obtained with the application of the Freundlich model, compared to the Langmuir model (Table 3). The maximum removal capacity (q_{max}) was almost double for Sr^{2+} compared to Cs^+ and Co^{2+}. Similarly, the binding affinity coefficient (b) was higher for Sr^{2+} compared to Cs^+ and Co^{2+}. The SRB culture in this study exhibited a superior Sr^{2+} binding capacity, compared to other studies in literature (Small et al., 1999; Parmar et al., 2000). In summary, results from the removal of Sr^{2+}, Cs^+, and Co^{2+} from single metal systems by SRB suggest that the sorption process conforms to a monolayer binding process, since the best fit was obtained with the Langmuir model (Kratochvil and Volesky, 1998).

3.4 Competitive binding of metals in binary metal solutions

The effect of a secondary metal ion on metal uptake by SRB was investigated in binary metal solutions to investigate the specificity of uptake process. The best fit for the binary-component equilibrium data was also achieved with the Langmuir isotherm. Table 4 shows the Langmuir parameters obtained for the removal of Sr^{2+}, Cs^+ and Co^{2+} from binary metal systems consisting of Sr/Cs, Cs/Co and Co/Sr. There was a 33% and 34% loss in the Sr^{2+}removal capacity (q_{max}) in the presence of Cs^+ and Co^{2+}. A 55% and 45% inhibition on

Cs^+ removal capacity was observed in binary component systems in the presence of Co^{2+} and Sr^{2+}, respectively. Among the binary systems investigated, Co^{2+} uptake was the most sensitive to the presence of Cs^+, where a 76% reduction of the sorption capacity (q_{max}) was observed. However, in the presence of Sr^{2+}, only a 9% loss of removal capacity was observed. With regard to the obtained results, the following inferences can be made (i)the present SRB culture demonstrated a high Sr^{2+} affinity, in all the binary metal solutions investigated in this study, (ii) possibly there are specialized binding-sites/processes specifically for divalent metals (Sr^{2+} and Co^{2+}) removal, as the co-existence of a secondary divalent cation resulted in minimal inhibitory effects, with the exception of the Co-Cs system, (iii) there seems to be no specific binding sites for the monovalent metal ion species (Cs^+), as maximum metal binding capacity was equally decreased in the presence of both divalent cations.

Metal binding by bacterial cells is a complex phenomenon, and cannot be fully explained by simple empirical models such as the Langmuir and Freundlich isotherms alone. The preliminary data on the kinetics of fission products removal by SRB in single metal systems and equilibrium binary component systems can only serve as the basis for further research on the sorption behaviour of a range of metals onto bacterial sorbents. Results from this study have shown that sulphate reducing bacteria displays a superior binding capacity compared to other bacterial biosorbents, in both single and binary metal systems. With further research, such knowledge is indispensable for the development and design of suitable processes for the clean-up of media contaminated with radionuclide and fission products, and particularly strontium.

4. CONCLUSION

Initial metal concentration and solution pH are important factors in determining metal removal kinetics. Chemisorption is the main rate limiting step for the removal of Sr^{2+}, Cs^+ and Co^{2+} from solution at different initial concentrations and pH values. Sulphate reducing bacteria used in this study exhibited a preferential order of metal ion equilibrium uptake efficiency in single metal systems in the order $Co^{2+} < Cs^+ > Sr^{2+}$. SRB demonstrated a specialized Sr^{2+} binding, as removal by the bacteria was least sensitive to the presence of other fission products. The present findings form an important aspect towards the development of effective strontium remediation strategies. Knowledge of the exact mechanisms involved in the observed high strontium removal capacity may be useful in engineering the removal of other harmful fission products and recovery of valuable radionuclides from wastewater of nuclear facilities.

6. NOMENCLATURE

b Langmuir affinity coefficient

C_{eq} equilibrium concentration (mg L^{-1})

C_i initial concentration (mg L^{-1})

k binding capacity constant

k_1 Lagergren constant for pseudo-first-order equation (min^{-1})

k_2 Lagergren constant for pseudo-second-order equation ($min^{-1} g\, mg^{-1}$)

q sorption uptake ($mg\, g^{-1}$)

q_{eq} metal uptake capacity ($mg\, g^{-1}$)

q_{max} maximum sorbate uptake ($mg\, g^{-1}$)

q_t concentration of ion species in the sorbent at time t ($mg\, g^{-1}$)

n Freundlich affinity coefficient

x dry weight of bacteria (g).

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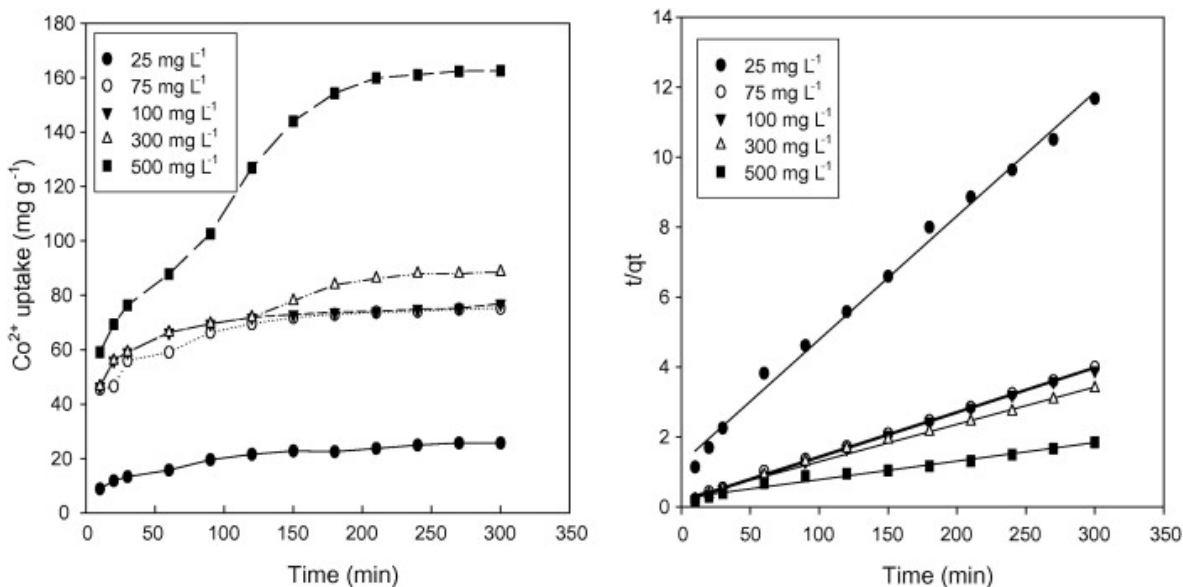
8. FIGURES

Figure 1: Effect of different initial metal concentrations on the removal of Sr^{2+} from solution by a sulphate reducing bacteria biomass and pseudo-second-order plot for the data.
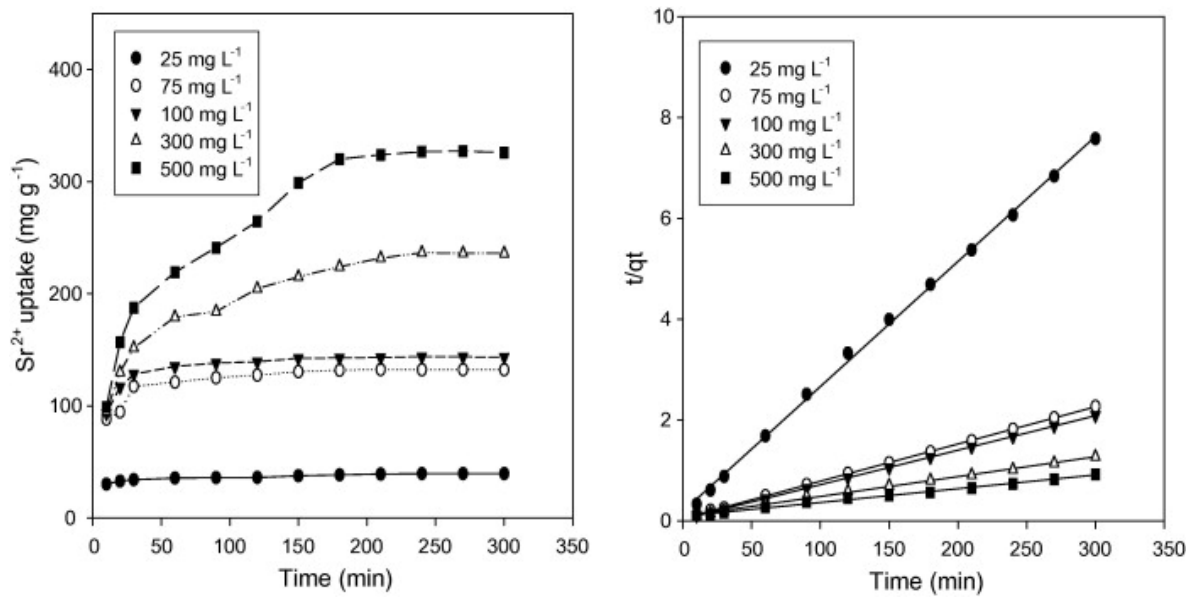
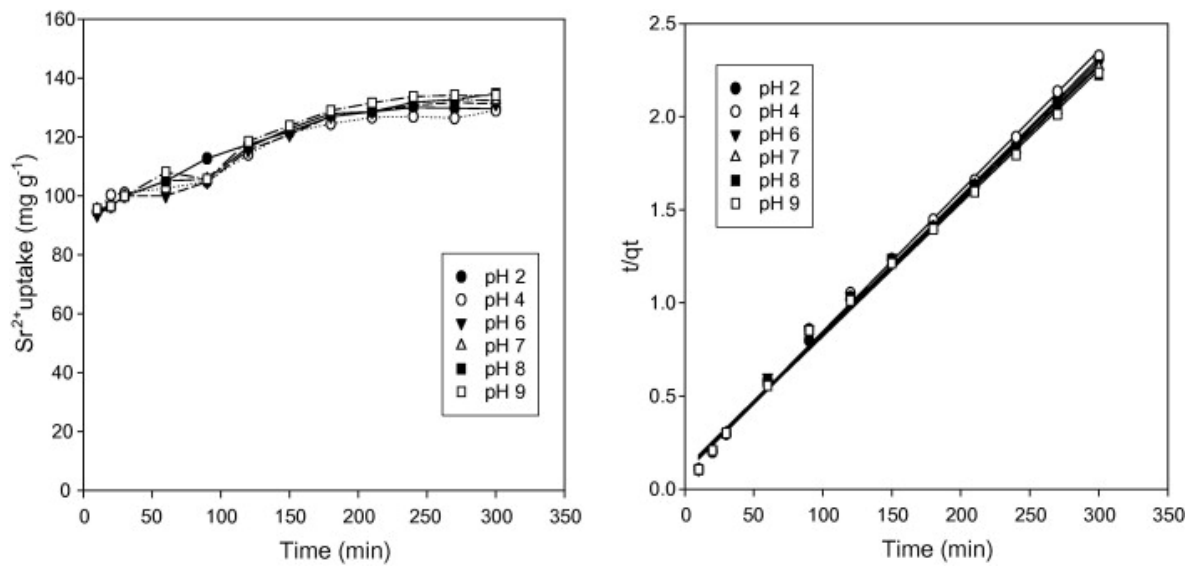**Figure 2**: Effect of different initial metal concentrations on the removal of Cs^+ from solution by a sulphate reducing bacteria biomass and pseudo-second-order plot for the data.
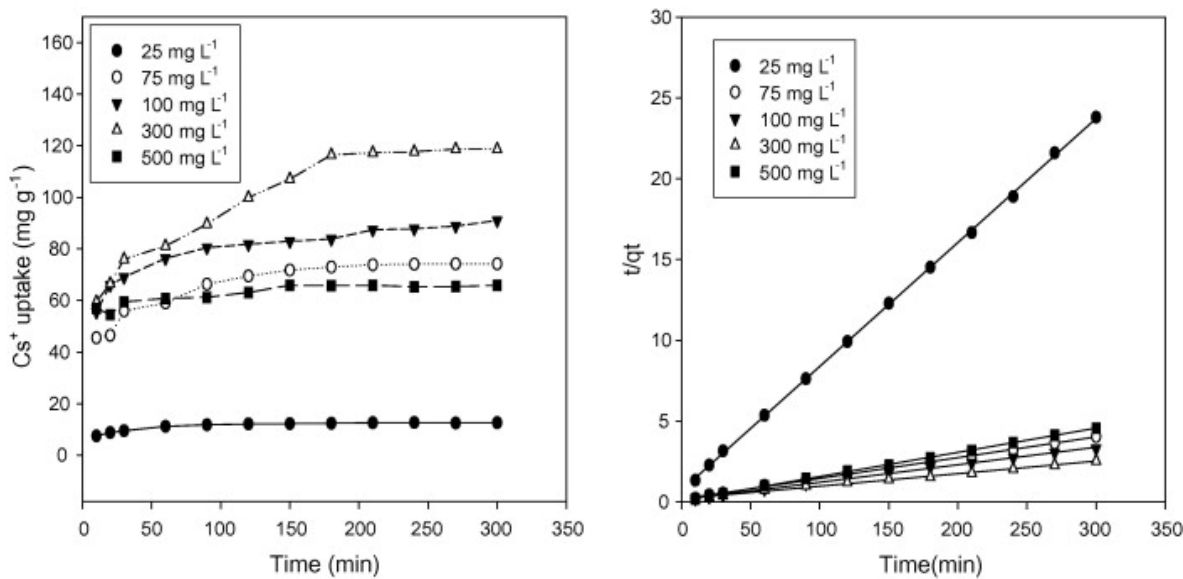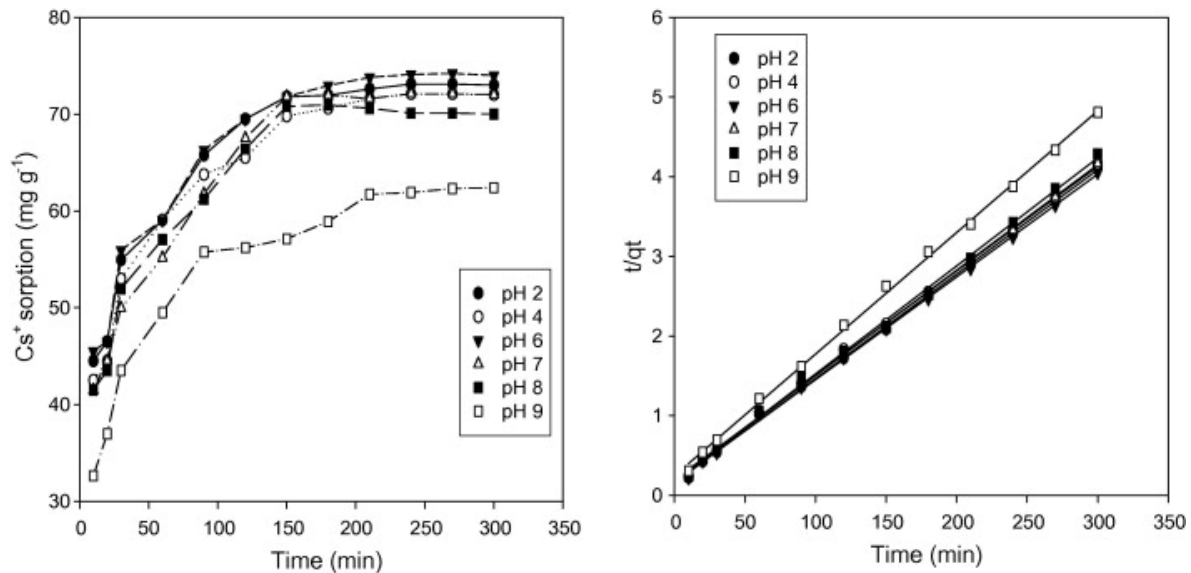

Figure 3: Effect of different initial metal concentrations on the removal of Co^{2+} from solution by a sulphate reducing bacteria biomass and pseudo-second-order plot for the data.

Figure 4: Effect of pH on the sorption behaviour of Sr^{2+} by a sulphate reducing bacteria biomass and pseudo-second-order plot for the data.

Figure 5: Effect of pH on the sorption behaviour of Cs^{+} by a sulphate reducing bacteria biomass and pseudo-second-order plot for the data.

Figure 6: Effect of pH on the sorption behaviour of Co^{2+} by a sulphate reducing bacteria biomass and pseudo-second-order plot for the data.
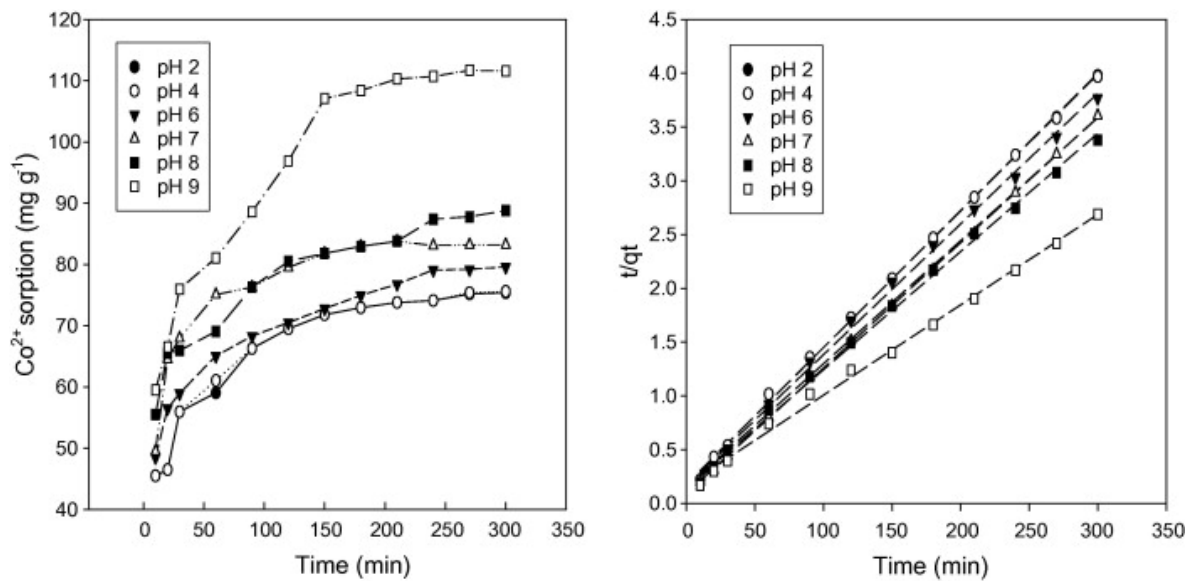
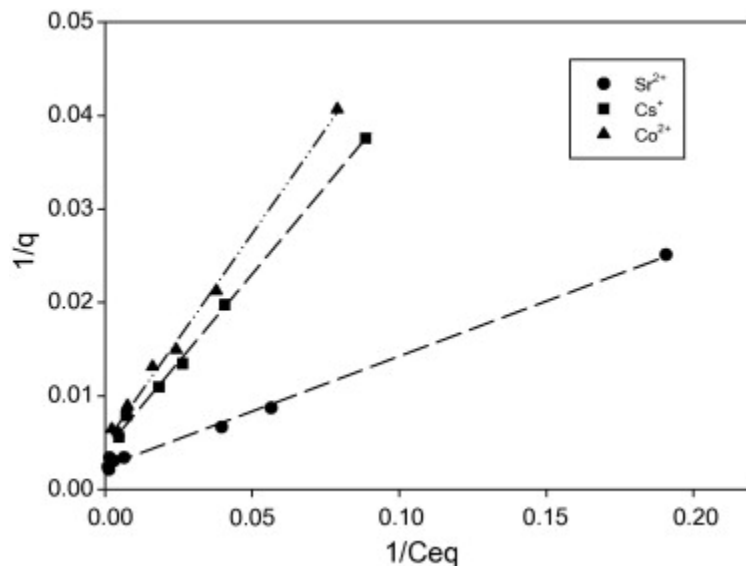**Figure 7**: Langmuir isotherm plot for Sr^{2+}, Cs^{+} and Co^{2+} sorption by a SRB biomass at a biomass density of 0.5g L^{-1}.

9. TABLES

Table 1 Pseudo-second order model parameters for the effect of initial concentration on the kinetics of Sr^{2+}, Cs^+ and Co^{2+} removal in single metal solutions.

Initial conc.	Sr^{2+}			Co^{2+}			Cs^+		
	q_{eq}	k_2 ($\times 10^{-4}$)	R^2	q_{eq}	k_2 ($\times 10^{-4}$)	R^2	q_{eq}	k_2 ($\times 10^{-4}$)	R^2
25	40.3	33.2	0.998	28.3	10.0	0.994	13.0	82.8	0.999
75	135.1	11.4	0.999	78.4	9.38	0.999	77.6	10.1	0.999
100	147.1	1.34	0.999	78.1	13.3	0.999	92.3	9.39	0.998
300	256.4	1.65	0.997	93.7	5.01	0.994	128.4	3.15	0.994
500	370.3	0.798	0.995	188.9	1.13	0.979	66.7	10.4	0.999

Table 2 Pseudo-second-order model parameters for the effect of pH on the kinetics of Sr^{2+}, Cs^+ and Co^{2+} removal in single metal solutions.

pH	Sr^{2+}			Co^{2+}			Cs^+		
	q_{eq}	k_2 ($\times 10^{-4}$)	R^2	q_{eq}	k_2 ($\times 10^{-4}$)	R^2	q_{eq}	k_2 ($\times 10^{-4}$)	R^2
2	134.6	6.374	0.998	78.6	9.202	0.999	76.4	10.9	0.999
4	132.5	6.191	0.997	78.7	9.076	0.999	75.5	9.81	0.999
6	137.1	4.845	0.996	82.3	8.846	0.998	77.0	10.3	0.999
7	137.8	5.044	0.996	85.8	14.7	0.999	76.3	8.77	0.998
8	138.9	4.751	0.996	91.1	8.26	0.998	73.4	11.0	0.999
9	139.8	4.873	0.996	119.1	4.247	0.996	65.5	9.42	0.999

Table 3 Langmuir and Freundlich model parameters for the removal of Sr^{2+}, Cs^+ and Co^{2+} in single metal solutions.

Metal ion	Langmuir model			Freundlich model		
	Q_{max} (mg g^{-1})	b ($\times 10^{-2}$)	R^2	k	n	R^2
Sr^{2+}	416.7	2.03	0.996	26.1	2.30	0.925
Cs^+	238.1	1.12	0.998	8.37	1.79	0.954
Co^{2+}	204.1	1.09	0.996	7.63	1.83	0.932

Table 4 Langmuir and Freundlich model parameters for the removal of Sr^{2+}, Cs^+ and Co^{2+} in binary metal solutions.

Metal system	Component	Langmuir			Freundlich		
		Q_{max} (mg g^{-1})	b ($\times 10^{-2}$)	R^2	k	n	R^2
Sr–Cs	Sr^{2+}	277.8	5.72	0.985	42.7	3.20	0.871
	Cs^+	107.5	3.06	0.938	18.0	3.34	0.670
Cs–Co	Cs^+	131.6	2.52	0.958	15.6	2.76	0.794
	Co^{2+}	49.3	3.40	0.986	7.55	2.89	0.847
Co–Sr	Co^{2+}	185.2	2.19	0.950	27.9	4.09	0.601
	Sr^{2+}	274.8	7.41	0.974	44.8	3.16	0.889