## Biosorption of Strontium Ions by Magnetically Modified Yeast Cells

Yan-Qin Ji[a]; Yan-Tao Hu[b]; Qing Tian[a]; Xian-Zhang Shao[a]; Jinying Li[b]; Mirka Safarikova[c]; Ivo Safarik[c]
[a] National Institute for Radiological Protection, Chinese Center for Disease Control and Prevention, Beijing, China [b] Department of Radiochemistry, China Institute of Atomic Energy, Beijing, China [c] Department of Nanobiotechnology, Institute of Systems Biology and Ecology, Academy of Sciences, Ceske Budejovice, Czech Republic

Online publication date: 15 June 2010

## PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis
Taylor & Francis Group

# Biosorption of Strontium Ions by Magnetically Modified Yeast Cells

Yan-Qin Ji,[1] Yan-Tao Hu,[2] Qing Tian,[1] Xian-Zhang Shao,[1] Jinying Li,[2] Mirka Safarikova,[3] and Ivo Safarik[3]

[1]*National Institute for Radiological Protection, Chinese Center for Disease Control and Prevention, Beijing, China*
[2]*Department of Radiochemistry, China Institute of Atomic Energy, Beijing, China*
[3]*Department of Nanobiotechnology, Institute of Systems Biology and Ecology, Academy of Sciences, Ceske Budejovice, Czech Republic*

**The sorption of $Sr^{2+}$ ions from aqueous solutions on magnetically modified fodder yeast (*Kluyveromyces fragilis*) cells and their subsequent desorption were studied. The $Sr^{2+}$ sorption increased with increasing pH and reached a plateau between pH 4.0 and 7.0. The changes of temperature slightly influenced the sorption process. The sorption values were $19.5 \, mg \, g^{-1}$ and $53.5 \, mg \, g^{-1}$ for $10 \, mg \, L^{-1}$ and $40 \, mg \, L^{-1}$ $Sr^{2+}$ solutions respectively after 20 min incubation at a pH higher than 4. The Langmuir isotherm was successfully used to fit experimental data; the maximum adsorption capacity was $140.8 \, mg \, g^{-1}$ under optimal conditions. The adsorbed $Sr^{2+}$ ions can be desorbed with nitric acid ($0.1 \, mol \, L^{-1}$).**

## INTRODUCTION

One of the most important problems during the reprocessing of spent fuels in the nuclear industry is the management and safe disposal of high level waste (HLW) and the uptake and separation of long-lived actinides radionuclides and fission products from nuclear waste solutions. Strontium-90, a β-emitter with 0.546 MeV energy, and a half-life of 28.6 years, is one of the most important fission products present in HLW. The content of strontium is roughly 10 times higher than that of cesium, and, as a heat-generator, it causes problems during depositing and vitrifying of HLW (1). Moreover, strontium behaves much like as calcium and deposits in plants by uptake from the soil; food recycle results in ^{90}Sr accumulation in the animal bones and teeth and damaging blood-producing cells (2). So, it is considered to be one of the most hazardous fission

products in the environmental protection field. Therefore, the separation of long-lived ^{90}Sr from HLW prior final disposal is important not only to reduce the volume of disposal waste and to simplify HLW vitrification, but also from the viewpoint of environment protection, to reduce the damage of all biological components.

Currently, simple and rapid methods for separation and determination of trace levels of strontium have become a focus in the field of radionuclide research. A number of methods have been reported, such as typical liquid/liquid extraction process (3,4), solid phase extraction (5,6), and other partitioning methods (7–9). Biosorption of heavy metal ions from aqueous solutions based on the use of biomass as an absorbent is considered to be a very promising process. This procedure has been successfully used for the removal of different types of organic and inorganic xenobiotics and metal ions, including strontium ones (2).

Recently magnetic separation techniques, which are usually based on the application of magnetically responsive composite materials have already found many important applications in various areas of biosciences, medicine, biotechnology, environmental technology, etc. (10,11). In order to simplify the separation processes, magnetically modified microbial biomass has been developed as an adsorbent and used for the separation of different kinds of compounds, such as heavy metal ions (12) or water soluble dyes (13).

Magnetically modified *Kluyveromyces fragilis* cells (fodder yeast) have been used recently as an efficient biosorbent for the removal of several organic dyes (14). This material is inexpensive and can be prepared in a simple way. Whole yeast cells and isolated cell walls are known to adsorb different metal ions efficiently (15,16). In this work magnetic fodder yeast cells were used as an adsorbent for the removal of $Sr^{2+}$ ions from aqueous solutions.

## MATERIALS AND METHODS
### Materials

Magnetically modified *Kluyveromyces fragilis* cells were prepared as described recently (14). Strontium nitrate standard (GBW(E) 080242) was obtained from National Research Center for Certified Reference Materials, Beijing, China. Common chemicals were provided by Alfa-Aesar, or Beijing Chemicals, China. Ultrapure water was obtained by Milli-Q System ($18.2\,M\Omega \cdot cm^{-1}$).

### Adsorption of $Sr^{2+}$ on Magnetically Modified *Kluyveromyces fragilis* Cells

Magnetically modified *Kluyveromyces fragilis* cells were suspended in ultrapure water (final concentration 13 mg (dry weight) $mL^{-1}$). Portions (0.05~4.9 mL) of strontium nitrate solution ($100\,mg\,L^{-1}$) and appropriate volumes of ultrapure water were mixed in 10 mL test tubes, then 0.1 mL of the yeast suspension was added under mixing and the total volume of the suspension was made up to 5.0 mL. The suspensions were mixed at appropriate temperature for 1 h. Subsequently, magnetic cells were separated from the suspension using a permanent magnet and concentration of $Sr^{2+}$ in the clear supernatant was measured using the Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Element2, Finnigan Ltd., Germany). The concentration of $Sr^{2+}$ was determined from the calibration curve. The amount of $Sr^{2+}$ adsorbed on a unit mass of adsorbent was calculated using the following formula (1):

$$Q_{eq} = \frac{(C_i - C_{eq}) \cdot V_1}{V_2 \cdot \alpha} \qquad (mg\,g^{-1}) \qquad (1)$$

where $Q_{eq}$ is the absorbed amount of $Sr^{2+}$ after reaching equilibrium, $C_i$ and $C_{eq}$ are the initial and equilibrium $Sr^{2+}$ concentrations in the aqueous phase, $V_1$ is the total volume of the suspension (5 mL), $V_2$ is the volume of the added magnetic yeast suspension (0.1 mL), and $\alpha$ is the dry mass of the adsorbent in 1 ml of suspension ($g\,mL^{-1}$); $\alpha$ was 0.013 during the experiments.

### Desorption of Strontium Ions

Desorption of bound $Sr^{2+}$ from magnetic *Kluyveromyces fragilis* cells was performed in $0.1\,mol\,L^{-1}$ $HNO_3$ solution under mixing at room temperature for 1 h. Then the suspension was separated using a permanent magnet and the concentration of $Sr^{2+}$ was determined in the clear supernatant using ICP-MS. To study the reusability of the biosorbent, the material after the desorption step was extensively washed with water and used again.

### Effect of pH Value and Temperature

The dependence of magnetic *Kluyveromyces fragilis* cells biosorption capacity on the pH value of strontium nitrate

solution (ranging from pH 1.0 to 7.0, determined with the pH meter PHS-3C, Shanghai REX Instrument Factory, China) was investigated at the $Sr^{2+}$ concentration $10\,mg\,L^{-1}$ and the incubation time 1 h at room temperature. Temperature dependence of biosorption was examined in the range 4~30°C at pH 7.0, incubation time 1 h and $Sr^{2+}$ concentration range $1\,mg\,L^{-1}$ to $40\,mg\,L^{-1}$.

## RESULTS AND DISCUSSION
### Effect of pH Value

The data in Fig. 1 indicate the effect of pH on the biosorption of $Sr^{2+}$. As can be seen, the biosorption capacity of magnetic yeasts for $Sr^{2+}$ increased with increasing pH. The biosorption value reached almost a plateau between pH 4.0 and 7.0, indicating that increased pH of the solution favors complexes formation between the ionized anionic groups on the yeast cells and $Sr^{2+}$. Lower affinity for $Sr^{2+}$ observed in low pH values (pH < 2.0) can be explained by the competition of protons and $Sr^{2+}$ for binding sites on the cell wall (17,18). Using $10\,mg\,L^{-1}$ $Sr^{2+}$ initial concentration and 20 min incubation time, the adsorption capacity of the magnetic biosorbent was $19.5\,mg\,g^{-1}$ under optimal conditions (pH > 4).

### Effect of Temperature

Temperature can influence adsorption of target compounds both in the positive and negative way. Figure 2 shows the influence of different temperature on the biosorption capacity of magnetic *Kluyveromyces fragilis* cells for $Sr^{2+}$. As can be seen, an increase of the temperature (examined in the range 4~30°C) caused gradual increase of adsorbent biosorption capacity; however, only a minor influence of temperature was observed and that is why

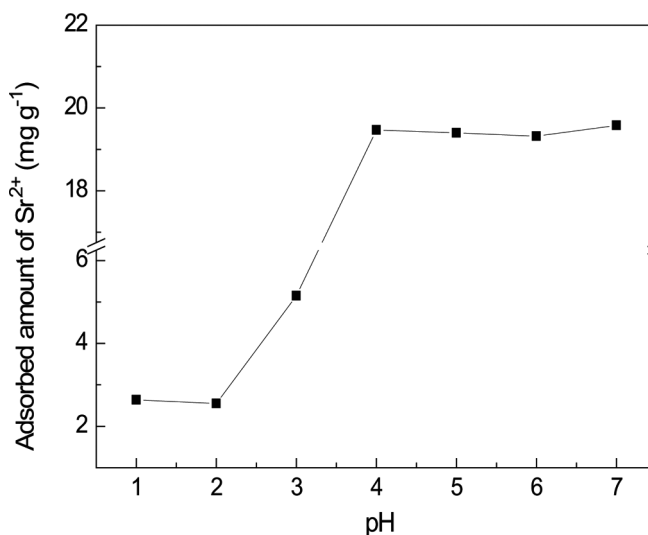FIG. 1. Effect of pH on biosorption of $Sr^{2+}$ on magnetically modified yeast cells ($Sr^{2+}$ concentration: $10\,mg\,L^{-1}$; temperature: 20°C; incubation time: 1 h).
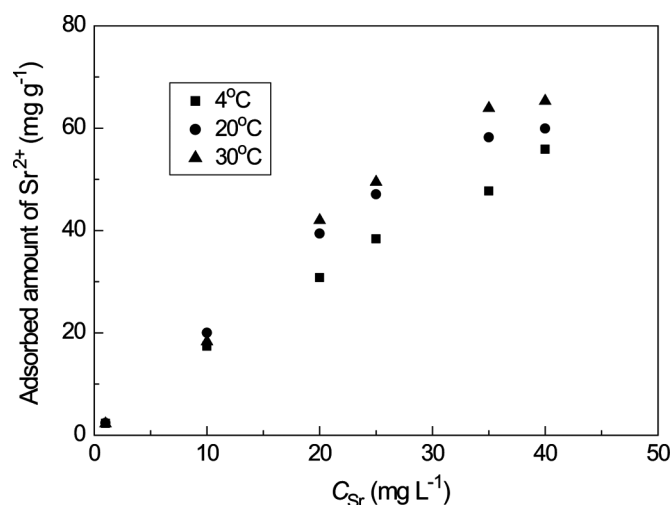
FIG. 2. Effect of temperature on $Sr^{2+}$ biosorption on magnetically modified yeast cells (pH: 7.0; incubation time: 1 h).

the subsequent experiments were performed at room temperature (20°C).

## Time Dependence of $Sr^{2+}$ Biosorption

The kinetics of biosorption of $Sr^{2+}$ by the magnetic *Kluyveromyces fragilis* cells from neutral solutions was investigated when the concentrations of $Sr^{2+}$ were $10 \, mg \, L^{-1}$ and $40 \, mg \, L^{-1}$ respectively. The results are shown in Fig. 3. As can be seen, the amount of $Sr^{2+}$ adsorbed on magnetic yeast cells quickly increased during the prolonged incubation time. Though the adsorption process reached equilibrium within $10 \sim 20 \, min$, an incubation time of 1 h was used for all subsequent experiments.

For 20 min incubation time, the biosorption capacity of magnetic yeast cells was $19.5 \, mg \, g^{-1}$ for $10 \, mg \, L^{-1}$ $Sr^{2+}$ solution and $53.5 \, mg \, g^{-1}$ for $40 \, mg \, L^{-1}$ $Sr^{2+}$ solution.

## $Sr^{2+}$ Desorption from Magnetic Yeast Cells

At the same time, desorption of bound $Sr^{2+}$ with $0.1 \, mol \, L^{-1}$ $HNO_3$ was studied. The desorption ratio was calculated from the amount of $Sr^{2+}$ absorbed on the magnetic yeast cells and the final concentration of $Sr^{2+}$ in the desorption solution. The courses of desorption, after charging the biosorbent with $Sr^{2+}$ from $10 \, mg \, L^{-1}$ and $40 \, mg \, L^{-1}$ solutions are shown in Fig. 3. As can be seen, the desorption process was fast and reached the equilibrium within $10 \sim 20 \, min$. After desorption, the amount of $Sr^{2+}$ still adsorbed accounted for 16.7% and 36.6% of the biosorption capacity of the adsorbent for $Sr^{2+}$ ions after loading with $10 \, mg \, L^{-1}$ and $40 \, mg \, L^{-1}$ solutions, respectively. These results confirm the influence of pH value on the adsorption process, i.e., that the $Sr^{2+}$ binding groups on the yeast cells exhibit lower affinity in lower pH values conditions.

Repeated adsorption/desorption cycles were performed to examine the reusability and metal recovery efficiency of the biosorbent. The $Sr^{2+}$ adsorption capacity decreased from 19.5 to about $13 \, mg \, g^{-1}$ at the third adsorption step after repeated loading with $10 \, mg \, L^{-1}$ solution and 20 min incubation time.

## Effect of $Sr^{2+}$ Concentrations

The effect of $Sr^{2+}$ initial concentrations (ranging from $1 \, mg \, L^{-1}$ to $100 \, mg \, L^{-1}$) on biosorption capacity of the magnetic *Kluyveromyces fragilis* cells was studied at pH 7 and contact time of 1 h, respectively (Fig. 4). The amount of $Sr^{2+}$ absorbed on the magnetically modified yeast cells
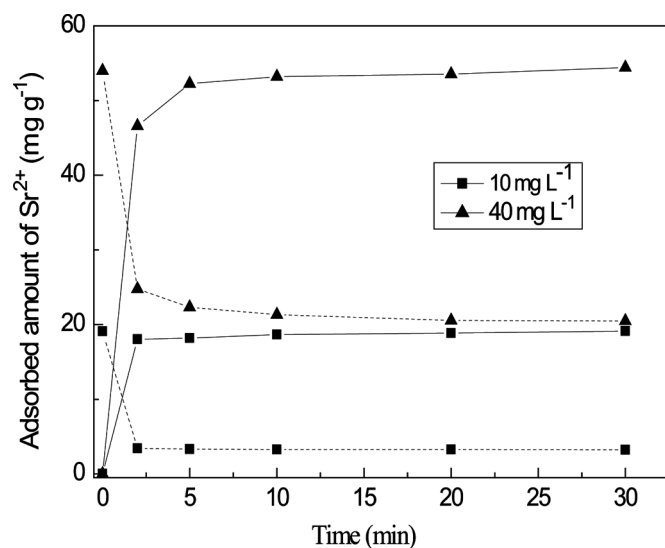


FIG. 3. $Sr^{2+}$ adsorption and desorption as a function of time, using magnetic yeast cells as adsorbent. —— adsorption curve; ...... desorption curve.
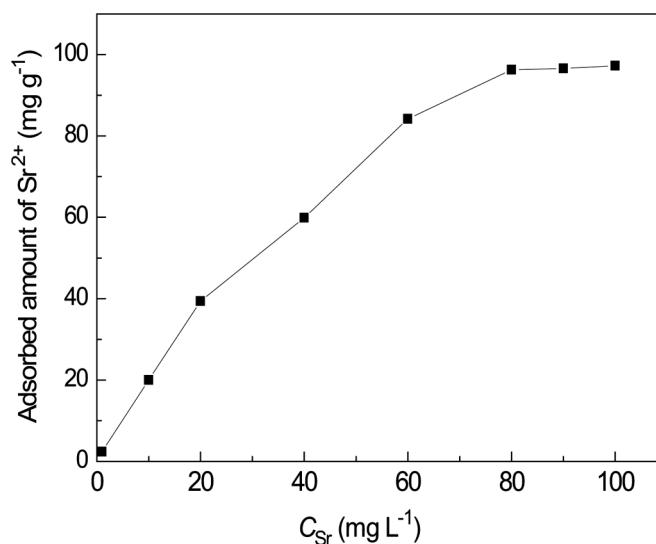


FIG. 4. Dependence of $Sr^{2+}$ adsorption on magnetic yeast cells on $Sr^{2+}$ initial concentration (pH: 7.0; temperature: 20°C; incubation time: 1 h).

quickly increased with the increase of the $Sr^{2+}$ concentration. When the $Sr^{2+}$ concentration increased to $80\,mg\,L^{-1}$ and more, the biosorption capacity remained constant, indicating saturation of the binding sites on the surface of the yeast cells. The cell walls of *Kluyveromyces fragilis* cells are composed from several types of biopolymers, such as glucan (28%), mannan (31%), proteins (13%), lipids (8%), chitin and chitosan (2%) (18,19). These compounds provide different types of groups (including metal-binding groups) such as carboxy-, hydroxyl-, amino-, sulfhydryl-, sulfate-, phosphate-, etc. $Sr^{2+}$ binding can be attributed to ion exchange, adsorption, complexation, microprecipitation, and crystallization processes occurring on the cell wall. According to the previous studies, $Sr^{2+}$ ions form stable bonds especially with nitrogen- or oxygen-ligands (20). The maximum biosorption capacity was $97.2\,mg\,g^{-1}$ for the magnetically modified yeast cells at the highest initial $Sr^{2+}$ concentration used ($100\,mg\,L^{-1}$). From the viewpoint of the adsorbed amount, the magnetically modified *Kluyveromyces fragilis* cells may be considered as a superior biosorbent for $Sr^{2+}$ and be appropriate to use in reprocessing processes to eliminate $Sr^{2+}$.

## Sorption Isotherms

To develop a possible large-scale "magnetic biomass" separation process, it is necessary to determine the biosorption capacity of the magnetic biocomposite. Previous literature has reported many isotherm models to calculate the maximum adsorption capacity of adsorbents. However, the most commonly used models are the Langmuir and Freundlich ones.

In the present study, Langmuir and Freundlich models have been used. A mathematical description of the Langumir isotherm is expressed as (2):

$$Q_{eq} = bQ_{max}C_{eq}/(1 + bC_{eq}) \qquad (2)$$

where $Q_{eq}$ (expressed in $mg\,g^{-1}$) is the amount of the adsorbed $Sr^{2+}$ ions per unit mass of magnetically modified cells at equilibrium and $C_{eq}$ (expressed in $mg\,L^{-1}$) is the equilibrium concentration of the unbound (free) metal ions. $Q_{max}$ is the maximum adsorption capacity ($mg\,g^{-1}$) and $b$ is a constant related to the enthalpy of adsorption (expressed in $L\,mg^{-1}$). The value of $Q_{max}$ represents a practical limiting adsorption capacity when the adsorbent surface is fully covered with metal ions.

The Freundlich isotherm describes a more complicated adsorption model where interactions occur between adsorbed molecules. The Freundlich isotherm is expressed as (3):

$$Q_{eq} = kC_{eq}^{1/n} \qquad (3)$$

where the constants $k$ and $1/n$ are characteristic constants, $k$ being related to the adsorption capacity. Constant $1/n$
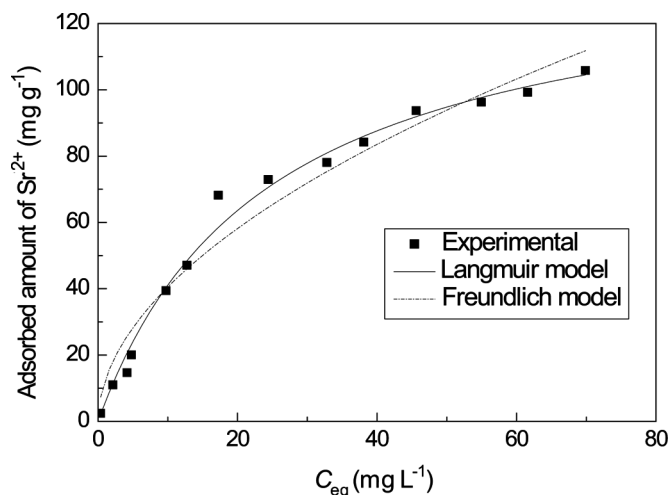


FIG. 5.   Equilibrium adsorption isotherms of $Sr^{2+}$ using magnetic yeast cells as adsorbent (pH: 7.0; temperature: 20°C; incubation time: 1 h).

represents the intensity of the reaction, with a value less than one indicating favorable adsorption.

The sorption isotherms for $Sr^{2+}$ binding on magnetic *Kluyveromyces fragilis* cells in neutral medium are given in Fig. 5. The biosorption capacity for $Sr^{2+}$ obtained from the experimental data was $97.2\,mg\,g^{-1}$ yeast cells using $100\,mg\,L^{-1}$ $Sr^{2+}$ initial concentration. The isotherm model parameters were obtained by non-linear least square fitting of the experimental data using Microcal Origin 6.0 program (Microcal Software Inc., 2000). The values of constants or binding parameters obtained by fitting Langmuir and Freundlich models to the experimental adsorption data obtained during adsorption of $Sr^{2+}$ on the magnetic *Kluyveromyces fragilis* cells, as well as the values of correlation coefficients are shown in Table 1. The Langmuir model fits well the experimental isotherm data and suggests that monolayer adsorption is the prevalent mechanism. The Langmuir model predicts a maximum biosorption capacity of $140.8\,mg\,g^{-1}$ (dry weight) for $Sr^{2+}$ binding on magnetic *Kluyveromyces fragilis* cells. This value is high, and is fully comparable or better when

TABLE 1
Calculated constants and correlation coefficients obtained by fitting Langmuir and Freundlich models to the experimental data

| Langmuir | Freundlich |
|---|---|
| $b = 0.041$ | $k = 12.16$ |
| $Q_{max} = 140.8$ mg/g | $1/n = 0.52$ |
| $R^2 = 0.9901$ | $R^2 = 0.9302$ |

TABLE 2

Comparison of maximum adsorption capacities $Q_{max}$ of studied magnetic yeast cells with other materials

| Adsorbent | $Q_{max}$ [mg g$^{-1}$] | Reference |
|---|---|---|
| Magnetic *Kluyveromyces fragilis* cells | 140.8 | This paper |
| *Amaranthus spinosus* root tissue powder | 12.89 | (21) |
| | 23.85 (NaOH treatment) | |
| Activated carbon | 44.4 | (22) |
| Mucilaginous seeds of *Ocimum basilicum* | 247 | (2) |
| Carbon material from pecan shells | 180 | (23) |
| *Shewanella alga* | 6.9 | (24) |
| *Shewanella putrefaciens* | 6.6 | (24) |
| Pakistani coal powder | 140 | (25) |
| Zeolite synthesized from fly ash | 85.5 | (26) |

compared with maximum adsorption capacities for other adsorbents described recently (see Table 2).

## CONCLUSIONS

Biosorption has become an important approach to remove heavy metals and radionuclides ions from aqueous solutions. In this paper magnetically modified yeast cells were used to study the biosorption and desorption of $Sr^{2+}$ from solutions. The results demonstrated that the adsorbed amount of $Sr^{2+}$ increased with the enhanced $Sr^{2+}$ concentration, reaching the plateau at around 80 mg L$^{-1}$ $Sr^{2+}$ initial concentration at 20°C and pH = 7. The biosorption capacity was affected by the pH value and constant adsorption was found at the pH range from 4 to 7. The biosorption process was fast and the equilibrium was reached in approximately 20 min. Desorption was carried out by using 0.1 mol L$^{-1}$ HNO$_3$ and approximately 80% of adsorbed $Sr^{2+}$ was released. In addition, magnetic modification of the yeast cells enabled their simple removal from the suspensions using a permanent magnet. This biosorbent exhibits superparamagnetic behavior at room temperature so the particles show magnetic properties when placed within a magnetic field, but retained no residual magnetism when removed from the field (14). From these results, we can draw a conclusion that magnetically modified yeast cells represent a promising adsorbent which could be used to concentrate and separate $Sr^{2+}$ ions from liquid high level waste originating during spent fuels reprocessing.

## REFERENCES

1. IAEA. (1993). Feasibility of separation and utilization of cesium and strontium from high level liquid waste. In: IAEA Technical Reports Series 356. Vienna.
2. Chakraborty, D.; Maji, S.; Bandyopadhyay, A.; Basu, S. (2007) Biosorption of cesium-137 and strontium-90 by mucilaginous seeds of *Ocimum basilicum*. *Bioresour. Technol.*, 98 (15): 2949–2952.
3. Moyer, B.A. (1996). In: *Comprehensive supramolecular chemistry, Volume 1: Molecular recognition: receptors for cationic guests*; Gokel, G. W., Vol. Ed.; Atwood, J. L. Davies, J. E. D. MacNicol, D. D., Voegtle, F., Exec. Eds.; Lehn, J.-M., Ed. Bd Chair; Pergamon: Oxford, 377–416.
4. Luo, H.M.; Dai, S.; Bonnesen, P.V. (2004) Solvent extraction of $Sr^{2+}$ and $Cs^+$ based on room-temperature ionic liquids containing monoaza-substituted crown ethers. *Anal. Chem.*, 76 (10): 2773–2779.
5. Horwitz, E.P.; Chiarizia, R.; Dietz, M.L. (1992) A novel strontium-selective extraction chromatographic resin. *Sol. Extr. Ion Exch.*, 10 (2): 313–336.
6. Zhang, A.; Wei, Y.Z.; Kumagai, M.; Koyama, T. (2004) Kinetics of the adsorption of strontium(II) by a novel silica-based 4,4′,(5′)-di (tert-butylcyclohexano)-18-crown-6 extraction resin in nitric acid medium. *J. Radioanal. Nucl. Chem.*, 262 (3): 739–744.
7. Visser, A.E.; Swatloski, R.P.; Reichert, W.M.; Griffin, S.T.; Rogers, R.D. (2000) Traditional extractants in nontraditional solvents: Groups 1 and 2 extraction by crown ethers in room-temperature ionic liquids. *Ind. Eng. Chem. Res.*, 39 (10): 3596–3604.
8. Miro, M.; Gomez, E.; Estela, J.M.; Casas, M.; Cerda, V. (2002) Sequential injection Sr-90 determination in environmental samples using a wetting-film extraction method. *Anal. Chem.*, 74 (4): 826–833.
9. Shamsipur, M.; Raoufi, F. (2001) Preconcentration and separation of trace amounts of strontium ions from alkali and alkaline earth metal ions using octadecyl silica membrane disks modified with decyl-18-crown-6 and its determination by flame atomic absorption spectrometry. *Mikrochim. Acta*, 137 (3–4): 163–167.
10. Safarikova, M.; Safarik, I. (2001) The application of magnetic techniques in biosciences. *Magn. Electric. Sep.*, 10: 223–252.
11. Safarik, I.; Safarikova, M. (2002) Magnetic nanoparticles and biosciences. *Mon. Chem.*, 133 (6): 737–759.
12. Yavuz, H.; Denizli, A.; Gungunes, H.; Safarikova, M.; Safarik, I. (2006) Biosorption of mercury on magnetically modified yeast cells. *Sep. Purif. Tech.*, 52 (2): 253–260.
13. Safarikova, M.; Pona, B.M.R.; Mosiniewicz-Szablewska, E.; Weyda, F.; Safarik, I. (2008) Dye adsorption on magnetically modified Chlorella vulgaris cells. *Fresenius Environ. Bull.*, 17 (4): 486–492.
14. Safarik, I.; Rego, L.F.T.; Borovska, M.; Mosiniewicz-Szablewska, E.; Weyda, F.; Safarikova, M. (2007) New magnetically responsive yeast-based biosorbent for the efficient removal of water-soluble dyes. *Enzyme Microb. Technol.*, 40 (6): 1551–1556.
15. Itoh, M.; Yuasa, M.; Kobayashi, T. (1975) Adsorption of metal-ions on yeast-cells at varied cell concentrations. *Plant Cell Phys.*, 16 (6): 1167–1169.
16. Patzak, M.; Dostalek, P.; Fogarty, R.V.; Safarik, I.; Tobin, J.M. (1997) Development of magnetic biosorbents for metal uptake. *Biotechnol. Technique*, 11 (7): 483–487.
17. Pardo, R.; Herguedas, M.; Barrado, E.; Vega, M. (2003) Biosorption of cadmium, copper, lead and zinc by inactive biomass of *Pseudomonas Putida*. *Anal. Bioanal. Chem.*, 376 (1): 26–32.

18. Godlewska-Zylkiewicz, B. (2006) Microorganisms in inorganic chemical analysis. *Anal. Bioanal. Chem.*, 384 (1): 114–123.

19. Brady, D.; Stoll, A.D.; Starke, L.; Duncan, J.R. (1994) Chemical and enzymatic extraction of heavy-metal binding polymers from isolated cell-walls of saccharomyces-cerevisiae. *Biotechnol. Bioeng.*, 44 (3): 297–302.

20. Guo, J.R.; Huang, H.X. (1985). *Analysis of Fission Product*; Atomic Energy Press: Beijing.

21. Chen, J.P. (1997) Batch and continuous adsorption of strontium by plant root tissues. *Bioresour. Technol.*, 60: 185–189.

22. Chegrouche, S.; Mellah, A.; Barka, M. (2000) Removal of strontium from aqueous solutions by adsorption onto activated carbon: Kinetic and thermodynamic studies. *Desalination*, 235: 306–318.

23. Shawabkeh, R.A.; Rockstraw, D.A.; Bhada, R.K. (2002) Copper and strontium adsorption by a novel carbon material manufactured from pecan shells. *Carbon*, 40: 781–786.

24. Small, T.D.; Warren, L.A.; Roden, E.E.; Ferris, F.G. (1999) Sorption of strontium by bacteria, Fe(III) oxide, and bacteria-Fe(III) oxide composites. *Environ. Sci. Technol.*, 33: 4465–4470.

25. Shaukat, M.S.; Sarwar, M.I.; Qadeer, R. (2005) Adsorption of strontium ions from aqueous solution on Pakistani coal. *J. Radioanal. Nucl. Chem.*, 265: 73–79.

26. Park, K.; Kam, S.; Ahn, B. (1998) Removal characteristics of strontium and cesium ions by zeolite synthesized from fly ash. *Appl. Chem.*, 2: 796–799.