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Use of the crosslinked copolymer functionalized with acrylic acid for the removal of strontium ions from aqueous solutions

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Abstract A crosslinked polyester resin containing acrylic acid as functional groups was synthesized and characterized by using FT-IR method. Adsorption behavior of strontium ions on the synthesized polyester resin was investigated as a function of sorptive concentration, time, temperature, and pH by using ICP-OES measurements. Adsorption data were analyzed by the modified Freundlich, Elovich, pseudo-first order and pseudo-second order kinetic models, by the Freundlich, Langmuir and Dubinin–Radushkevich isotherms and by the thermodynamic parameters such as enthalpy ($\Delta H°$), entropy ($\Delta S°$) and free energy change ($\Delta G°$).

Keywords Polyester resin functionalized with acrylic acid · Thermodynamic and kinetic parameters · Adsorption isotherms · Strontium ions

Introduction

The radioactive or toxic metal ions such as U(VI), Sr(II) and Cs(I) cause progressive or irreversible rental injury and in acute cases may lead to kidney failure and dead [1–11]. The fission products such as strontium and cesium are important contaminants in nuclear waste solutions or wastes [1, 11–17]. Radioactive strontium is produced not only as a waste fission product from plants, but also in the processing of nuclear fuels. Radioactive ^{90}Sr has a typical high value of radioactivity of 3000–4500 μCi ^{90}Sr per liter and half life of 28 years. ^{90}Sr once incorporated into bone continues to β-irradiate localized tissues with the eventual development of bone sarcomas and leukemias [11, 13, 16, 17]. For this reason, the removal of radioactive strontium ions from waste solutions or wastes is of great importance.

Many separation and preconcentration techniques, such as, chemical precipitation, ion-exchange, solvent extraction and sorption on inorganic or organic solids have been developed to remove toxic or radioactive metal ions from aqueous waste solutions or wastes [18–21]. At present time, there is an increasing effort for removing toxic or radionuclide contaminants from aqueous waste solutions or wastes by using various polymeric adsorbents [22–25]. It is known that the use of polymeric adsorbents to remove toxic or radioactive metal ions from aqueous waste solutions or wastes pose many advantages for controlling adsorption capacity and may present selective adsorption of metal ions from waste solutions [25–28]. For these purposes, many studies have been performed using polymers or polymeric networks having functional groups such as amideoximes and phosphoric, methacrylic, itaconic, acrylic, succinic, iminoacetic acid and hydroxamic acids for the removal of metal ions from waste solutions [26–37].

Unsaturated polyester polymer or copolymer dissolved in reactive monomer, such as, styrene can be copolymerized into infusible, insoluble tree dimensional networks by using an organic peroxide or hydroperoxide [9, 38, 39]. Decomposition of peroxide or hydroperoxide is accomplished either thermally or by the addition of chemical reducing agents, such as, *N*,*N*-dimethylaniline or cobalt octoate [9, 40–43]. In this study, the unsaturated polyester resin containing the monomers of styrene and acrylic acid was chosen because of high hydrolytic stability of its ester linkage and it is commercially available and cheap compound. The copolymer bearing acrylic or methacrylic acid functional groups has been chosen as chelating compound

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because of its well-known chelating ability with metal ions in aqueous solutions [9, 11, 25, 32, 33]. Adsorption mechanism between strontium ions and acrylic acid functional groups in the unsaturated polyester resin involves chemical reaction and mass transport processes in liquid phase, diffusion across the liquid film surrounding the solid particles, diffusion in macropores and micropores. The sorption data has been analyzed by the sorption isotherms of the Freundlich, Langmuir, and Dubinin–Radushkevich (D–R) isotherms. Adsorption capacity and free energy change have been determined by using D–R isotherm. In order to examine the fitting of adsoption data to the kinetic models, various kinetic models, such as, the modified Freundlich, Elovich, pseudo-first order and pseudo-second order kinetic models have been used to characterize the adsorption kinetics of different ion-exchangers as described in previous studies [44–48].

In this study, the Sr(II) adsorption on the crosslinked polyester resin bearing acrylic acid functional groups from aqueous solutions were analyzed as a function of adsorption parameters such as the amount of adsorbent, initial strontium concentration, pH of solution, contact time and temperature. Adsorption data changing with adsorption time were used to test for the kinetic models of the modified Freundlich, Elovich, pseudo-first order and pseudo-second order kinetic models. The fitting of adsorption data to the kinetic equations and the constants in these equations were analyzed. Adsorption data obtained from experimental results as depending on strontium concentration were used to analyze the fitting of adsorption data to the adsorption isotherms of the Freundlish, Langmuir and D–R isotherms. The constants in the adsorption isotherms were determined and adsorption capacity and free energy change (E) were calculated by using the D–R isotherm. The enthalpy ($\Delta H°$), entropy ($\Delta S°$) and free energy change ($\Delta G°$) were calculated by using adsorption data obtained from experimental results as depending on temperature.

Experimental

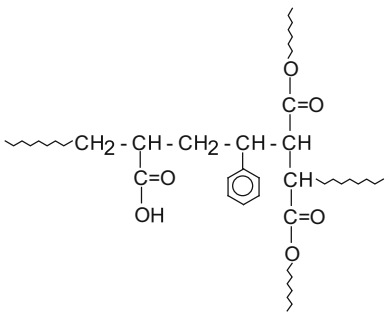
Standard polyester resin (Polipol 353, Poliya), acrylic acid (Merck), cobalt octoate solution containing 1 % Co as weight percentage in toluene (Ege Kimya), methylethylketone peroxide, MEKp (Butanox M60, Akzo Nobel) and strontium nitrate (Merck) were used without further treatment.

80 g solution of unsaturated polyester resin in styrene monomer (Polipol 353) and 20 g of acrylic acid by using initiator system of 0.5 mL of cobalt octoate solution containing 1 % Co as weight percentage and 1 mL of methylethylketone peroxide, MEKp (Butanox M60) were used in a typical synthesis [9] and the crosslinked copolymer having chemical structure given in Scheme 1 was obtained and used to remove Sr(II) from aqueous solutions.

FT-IR spectra of crosslinked polyester resin containing acrylic acid functional groups and the same polymer adsorbed Sr(II) from aqueous solution are shown in Fig. 1. As can be seen from Fig. 1, curve 1, the band observed at 3550 cm^{-1} shows the O–H stretching vibration in –COOH group. The C=O in ester linkage or carbonyl group are observed at 1730 cm^{-1}. The bands at 1397 and 1460 cm^{-1} indicate O–H bending and vibration bending of C–O in C–O–H plane. The C–O–C asymmetric stretching in ester group is observed at 1150 cm^{-1}. The sharp bands observed at 1600, 1497 and 1456 cm^{-1} are the characteristic for –COOM bond due to complexation of carboxyl groups of the crosslinkled polyester resin with strontium ions (Fig. 1, curve 2).

The crosslinked polyester resin functionalized with acrylic acid was ground to the powder and the particles which are smaller than 150 μm of diameter were separated to use them in the adsorption measurements of strontium ions from aqueous solutions. The scanning electron microscopy image of the particles of the crosslinked polyester resin functionalized with acrylic acid was shown in Fig. 2. As seen from Fig. 2, the diameter of the biggest particle is lower than 150 μm.

The effects of following parameters for the adsorption of Sr(II) on the crosslinked polyester resin bearing acrylic acid functional groups were scrutinised. These parameters are: (1) the amount of adsorbent ($m_{\text{Adsorbent}} = 0.01$, 0.02, 0.03, 0.04, 0.05, 0.06 and 0.07 g) at constant initial Sr(II) concentration of 11.01 ppm, time ($t = 60$ min) and temperature ($T = 293$ K)), (2) initial Sr(II) concentration ($C_{Sr(II)} = 5.13$, 9.99, 26.08, 52.12 and 103.90 ppm for various temperatures ($T = 283$, 293, 303 and 313 K) at constant amount of adsorbent ($m_{\text{Adsorbent}} = 0.05$ g) and contact time ($t = 60$ min)), (3) contact time ($t = 1$, 2, 3, 5, 10, 15, 30 and 60 min for $T = 293$ K, $m = 0.05$ g and various Sr(II) concentrations), (4) temperature ($T = 283$, 293, 303 and 313 K for $t = 60$ min, $m_{\text{Adsorbent}} = 0.05$ g



Scheme 1 The chemical structure of synthesized crosslinked polyester resin

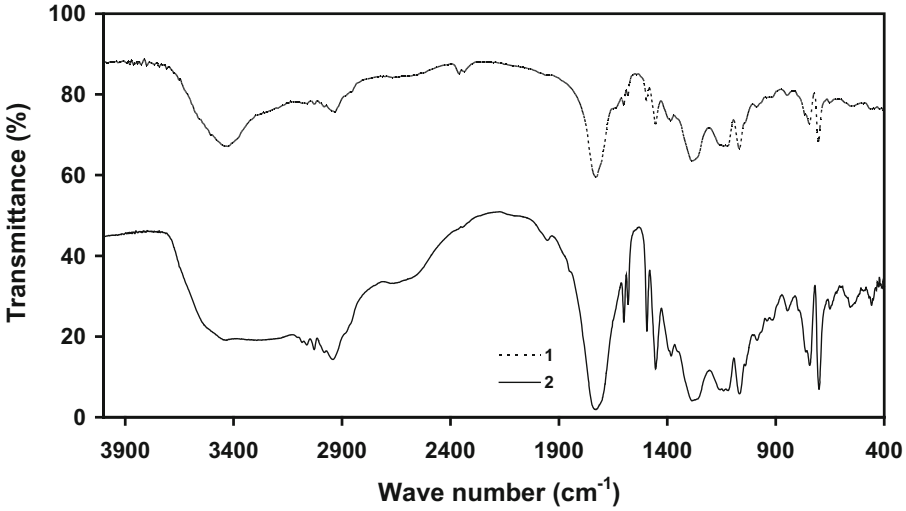


Fig. 1 FT-IR spectra of polyester resin containing acrylic acid functional groups (1) and the same polymer adsorbed Sr(II) from aqueous solution (2)

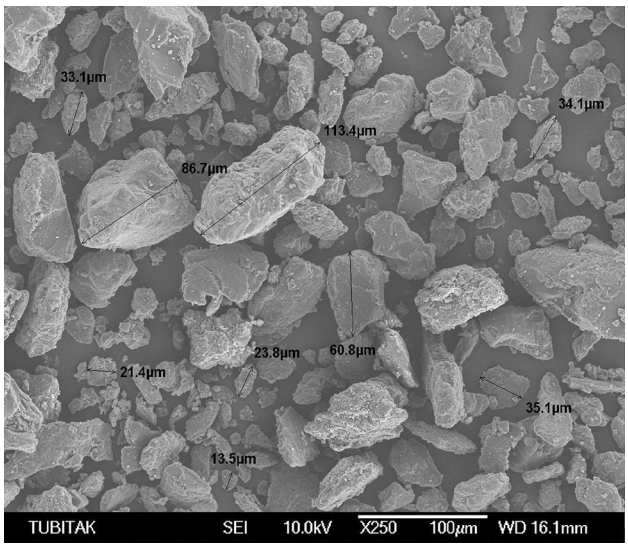


Fig. 2 SEM imagine of particles of the crosslinked polyester resin functionalized with acrylic acid used in Sr(II) adsorption measurements

and various Sr(II) concentrations of 5.13, 10.01 and 26.08 ppm) and (5) pH of solution from 1.51 to 8.51 at 295 K for $m_{\text{Adsorbent}} = 0.05$ g and $C_{\text{Sr(II)}} = 10.83$ ppm. Batch adsorption method was used in the Sr(II) adsorption experiments.

During Sr(II) adsorption on the crosslinked polyester resin containing acrylic acid functional groups, 0.05 g of polymer was immersed into 5 mL of Sr(II) solution and the mixture was shaken for definite time, temperature and pH. The copolymers were separated from the solution by centrifugation at 3500 rpm for 20 min. Sr(II) adsorption was calculated by determining the amount of Sr(II) in solution at beginning and after definite adsorption time by means of ICP-OES measurements. The percentage (Ads.%) of adsorption, distribution coefficients (K_D), the concentrations of C_t and C_e and the amounts of q_t and q_e were calculated by the equations given below:

$$\text{Ads.}\% = \frac{C_0 - C_e}{C_0} \times 100 \quad (1)$$

$$K_D = \frac{C_0 - C_e}{C_e} \times \frac{V}{m} \quad (2)$$

$$q_t = (C_0 - C_t) \times \frac{V}{m} \quad (3)$$

$$q_e = (C_0 - C_e) \times \frac{V}{m} \quad (4)$$

$$C_t = (1 - \text{Ads.}\%\ /100) \times C_0, \quad (5)$$

where C_0 is the initial Sr(II) concentration (mol/L), K_D is the batch distribution coefficient (mL/g), C_t and C_e are the Sr(II)) concentrations (mol/L) in solutions at time, t and at equilibrium at 60 min, respectively. q_t and q_e are the amount of adsorbed Sr(II) in terms of mol/g on the crosslinked copolymer at time, t and at equilibrium ($t = 60$ min), respectively. V is the volume of Sr(II) solution (mL) in the adsorption experiment and m is the weight of adsorbent used in adsorption measurements (g).

Results and discussion

The effect of the amount of adsorbent

Various amounts of the crosslinked copolymer containing acrylic acid functional groups was mixed with 5 mL of Sr(II) solution (11.01 ppm) at 293 K and pH 4.48 (Fig. 3). As can be seen from Fig. 3, at 11.01 ppm Sr(II) concentration, with increasing the amount of adsorbent from 0.01 to 0.07 g in the adsorption measurement of Sr(II) at 293 K, it was observed that the adsorption percentage increased

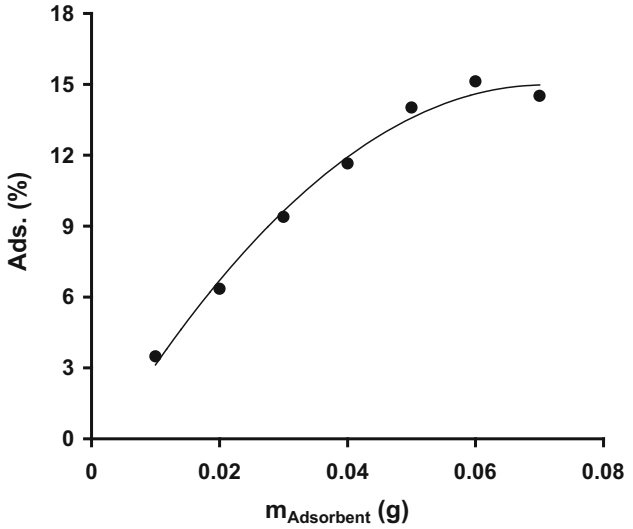


Fig. 3 The effect of adsorbent mass on the adsorption percentage for the Sr(II) adsorption on the crosslinked polyester resin bearing acrylic acid functional groups from aqueous solution for 11.01 ppm of initial Sr(II) concentration at constant temperature of 293 K and adsorption time of $t = 60$ min

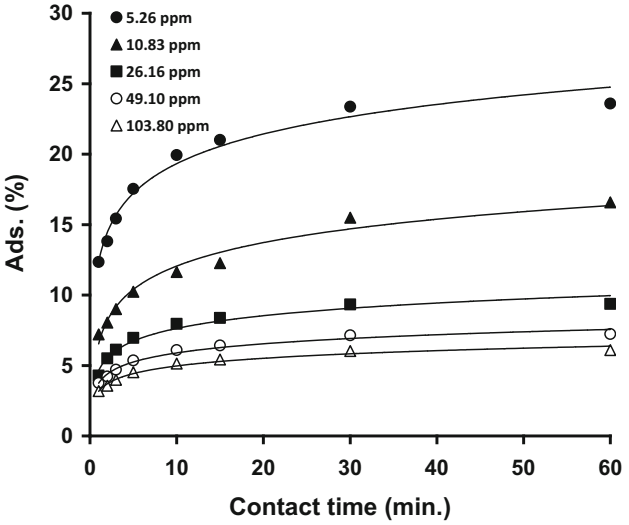


Fig. 4 The effect of contact time on the percentage of Sr(II) adsorption for the croslinked polyester resin bearing acrylic acid functional groups. Initial Sr(II) concentration of 5.26 ppm (*filled circle*), 10.83 ppm (*filled triangle*), 26.16 ppm (*filled square*), 49.10 ppm (*open circle*) and 103.80 ppm (*open triangle*) at 293 K of adsorption temperature

and reached an equilibrium at the range of $m_{\text{Copolymer}} =$ 0.05–0.07 g. For this reason, 0.05 g of adsorbent which has an adsorption efficiency of 15.83 % was used in further adsorption experiments to investigate the dependence of Sr(II) adsorption to the parameters, such as, initial Sr(II) concentration, contact time, temperature and pH of solution by using the crosslinked copolymer bearing acrylic acid functional groups as adsorbent.

The effect of contact time

The dependence of Sr(II) adsorption on the contact time was illustrated in Fig. 4 for Sr(II) adsorption on the crosslinked copolymer bearing acrylic acid functional groups from aqueous solutions at initial Sr(II) concentrations from 5.26 to 103.80 ppm at 293 K. As seen from Fig. 4, With increasing contact time, the percentage of the adsorbed Sr(II) on the crosslinked polyester resin increased and reached at equilibrium after 30 min. As described in previous investigations, a rapid initial Sr(II) adsorption on the crosslinked polyester resin has been followed by a steady and at later stages adsorption reached an apparent plateau in 30 min.

The modified Freundlich kinetic model

The modified Freundlich or fractional power kinetic equations were written by the Eq. (6) given below [4, 9, 32, 49]:

$$q_t = at^b. \tag{6}$$

The linearized form of Eq. (6) can be written by following Eq. (7).

$$\ln q_t = \ln a + b \ln t, \tag{7}$$

where q_t is the amount of Sr(II) adsorbed by crosslinked polyester resin functionalized with acrylic acid at time, t. The a and b are the constant for the modified Freundlich kinetic equation. Figure 5 shows a plot of q_t against ln t of

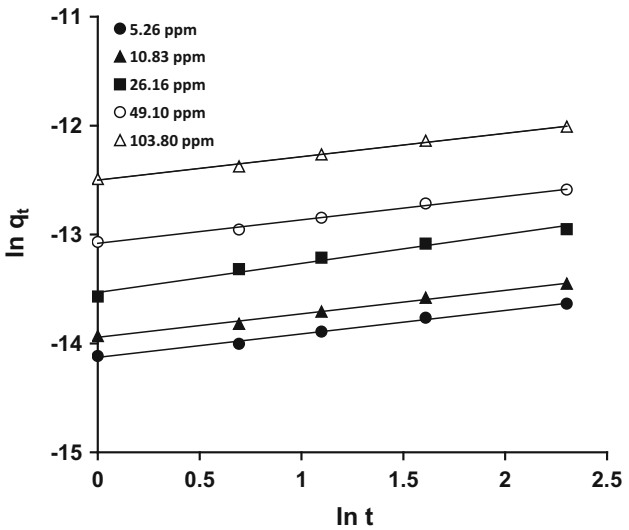


Fig. 5 The fitting of adsorption data on the modified Freundlich adsorption model for initial Sr(II) concentration of 5.26 ppm (*filled circle*, 10.83 ppm (*filled triangle*), 26.16 ppm (*filled square*), 49.10 ppm (*open circle*) and 103.80 ppm (*open triangle*) at 293 K

Table 1 The kinetic constants obtained from the modified Freundlich and Elovich kinetic equations for the Sr(II) adsorption on crosslinked polyester resin functionalized with acrylic acid from aqueous solutions at 293 K

C_0 (ppm)	The Modified Freundlich kinetic model			The Elovich kinetic model		
	a	b	R	B	A	R
5.26	7.316×10^{-7}	0.215	0.993	2×10^{-7}	1.66×10^{8}	0.986
10.83	8.785×10^{-7}	0.216	0.992	2×10^{-7}	4.50×10^{8}	0.987
26.16	13.280×10^{-7}	0.267	0.980	5×10^{-7}	1.48×10^{7}	0.998
49.10	20.840×10^{-7}	0.216	0.992	6×10^{-7}	4.67×10^{7}	0.986
103.80	37.230×10^{-7}	0.215	0.993	10×10^{-7}	5.46×10^{7}	0.987

the modified Freundlich kinetic equation for the Sr(II) adsorption on the crosslinked polyester resin for various initial Sr(II) concentrations from 5.26 to 103.80 ppm at constant temperature (293 K). As seen from Fig. 5, there is a linear relationship between ln q_t and ln t values. The values of a, b and correlation coefficient (R) were determined for various initial Sr(II) concentration at 293 K (Table 1). When the modified Freundlich kinetic model was applied to the adsorption data, the slightly better correlation coefficients ($0.980 \leq R \leq 0.993$) were attained.

The Elovich kinetic model

The Elovich or Rodinky–Zeldovich kinetic equation is generally expressed as follows [4, 9, 32, 49, 50]:

$$\frac{dq_t}{dt} = A \exp(-Bq_t), \tag{8}$$

where q_t is the amount of Sr(II) adsorbed by the crosslinked polyester resin functionalized with acrylic acid at time, t. A is the initial Sr(II) adsorption rate (mol/g min) and B is the adsorption constant (g/mol). The linearized form of the Elovich Eq. (8) can be written as follows:

$$q_t = B \ln(AB) + B \ln t, \tag{9}$$

when the linear plot of q_t versus ln t is drawn, the constants of A and B can be determined from the values of slope and intercept. In this case, The linear relationships were obtained between the adsorbed Sr(II) (q_t) on the crosslinked copolymer and ln t for the lines given in Fig. 6. When adsorption data were applied to the Elovich equation, the calculated values of A, B and correlation coefficients were listed in Table 1. As can be seen from Fig. 6 and Table 1, slightly low correlation coefficients have been obtained. When initial Sr(II) concentration increased from 5.26 to 103.80 ppm, The values of B increased from 2×10^{-7} to 10×10^{-7} and the values of A decreased from 16.6×10^{7} to 5.46×10^{7} respectively. The quality of A in the Elovich equation is the equivalent to the initial gradient which varied with different Sr(II) concentrations.

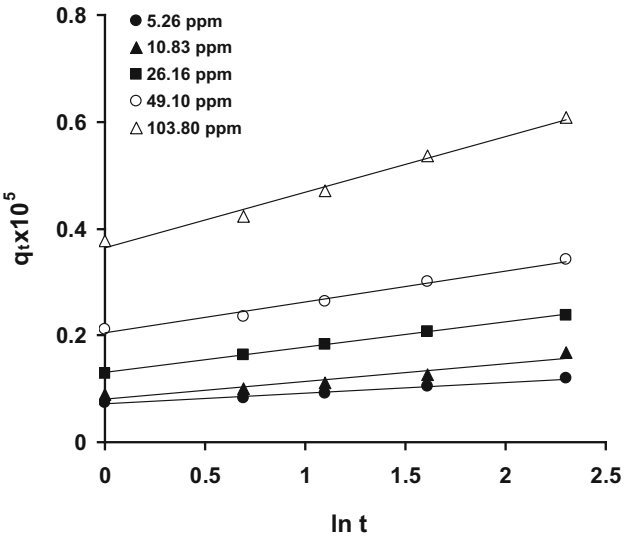


Fig. 6 The relation between q_t and ln t in the linearized Elovich adsorption equation for the Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid at 293 K. The initial Sr(II) concentrations are 5.26 ppm (*filled circle*), 10.83 ppm (*filled triangle*), 26.16 ppm (*filled square*), 49.10 ppm (*open circle*) and 103.80 ppm (*open triangle*) at 293 K

The pesudo-first order kinetic model

The pseudo-first order kinetic model describes a reversible equilibrium between the ions in solution and those adsorbed on solid phase [4, 9, 32, 50–54]. In order to investigate the sorption rate of Sr(II) on the crosslinked polyester resin, the following pseudo-first order equation given below was used:

$$\frac{dq_t}{dt} = k(q_e - q_t), \tag{10}$$

where q_e and q_t are the amounts of uranium ions adsorbed by the crosslinked polyester resin at equilibrium and at time, t, respectively. The k (1/min) is the rate constant for pseudo-first order kinetic equation. The linearized form of the pseudo-first order kinetic equation can be written below.

$$\ln(q_e - q_t) = \ln q_e - kt. \tag{11}$$

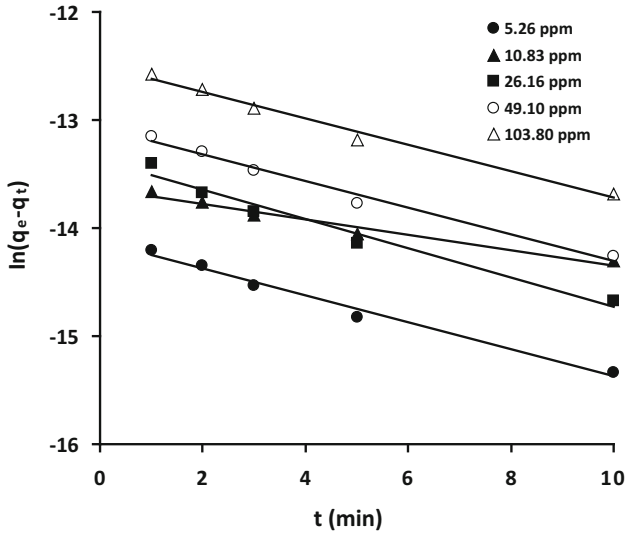


Fig. 7 The dependence of adsorption data $\ln(q_e - q_t)$ to time, using pseudo-first order kinetic model as a function of initial Sr(II) concentrations of 5.26 ppm (*filled circle*), 10.83 ppm (*filled triangle*) and 26.16 ppm (*filled square*) 49.10 ppm (*open circle*) and 103.80 ppm (*open triangle*) at 293 K

Figure 7 shows the results of the Sr(II)) adsorption on the crosslinked polyester resin for initial Sr(II) concentrations from 5.26 to 103.80 ppm at 293 K The linear relationships between ln $(q_e - q_t)$ and t have been checked for various initial Sr(II) concentrations of 5.26, 10.83, 26.16, 49.10 and 103.80 ppm at 293 K. Fairly low correlation coefficients ($0.906 \leq R \leq 0.986$) have been found and the adsorption rate constants were determined at the range of $7.02 \times 10^{-2} \leq k \leq 13.53 \times 10^{-2}$ in the term of min^{-1} for different initial Sr(II) concentration from 5.26 to 103.80 ppm at constant temperature of 293 K (Table 2).

The pseudo-second order kinetic model

The pseudo-second order kinetic model defines that the rate controlling mechanism formed by chemical reaction for the sorption of metal ions on adsorbents [4, 9, 32, 49–51, 54–58]. In order to describe Sr(II) sorption on the crosslinked polyester resin by using the initial Sr(II) concentrations from 5.26 to 103.80 ppm at constant temperature ($T = 293$ K), the adsorption data obtained from the batch adsorption experiments have been analyzed using the pseudo-second order kinetic equation given below.

$$\frac{dq_t}{dt} = k(q_e - q_t)^2, \tag{12}$$

where q_e and q_t are the amounts of Sr(II) adsorbed by the crosslinked polyester resin bearing acrylic acid functional groups at equilibrium and at time, t, respectively. The k (L/mol s) is the rate constant for pseudo-second order kinetic equation. By separating variables and integrating the equation for initial limit, $t = 0$, $q_t = 0$, the following Eq. (12) is obtained which is the integrated rate law of pseudo-second order reaction.

$$\frac{1}{q_e - q_t} = \frac{1}{q_e} + kt. \tag{13}$$

This Eq. (13) can be rearranged to obtain the following linear form illustrated in earlier studies:

$$\frac{t}{q_t} = \frac{1}{kq_e^2} + \frac{1}{q_e}t. \tag{14}$$

The kinetic plots of t/q_t versus t for Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid are represented in Fig. 8. As can be seen from Fig. 8, there is a linear relationship between t/q_t and t values for Sr(II) adsorption on the crosslinked copolymer by using the initial Sr(II) concentration from 5.26 to 103.80 ppm at constant temperature of 293 K. The adsorption rate constants (k), initial adsorption rates ($h = kq_e^2$) and equilibrium adsorption capacity (q_e) calculated from slope and intercept of linear lines given in Fig. 8 were listed in Table 2. As can be seen from Fig. 8 and Table 2, The data-fits for Sr(II) adsorption on the crosslinked polyester resin have resulted in high correlation coefficients ($0.997 \leq R \leq 0.999$), when the pseudo-second order kinetic model was employed to the experimental results. The goodness of the fit of Sr(II) adsorption data to the pseudo-second order kinetic model indicates that Sr(II) adsorption on the crosslinked polyester

Table 2 The kinetic constants obtained from the pseudo-first order and pseudo-second order kinetic equation for the Sr(II) adsorption on crosslinked polyester resin functionalized with acrylic acid from aqueous solutions at 293 K

C_0 (ppm)	Pseudo-first order kinetic model		Pseudo-second order kinetic model			
	k (min^{-1})	R	q_e (mmol/g)	k (g/min/mmol)	h (mmol/min/g)	R
5.26	12.45×10^{-2}	0.986	1.31×10^{-3}	7.123×10^{2}	1.223×10^{-3}	0.997
10.83	7.02×10^{-2}	0.966	1.58×10^{-3}	5.890×10^{2}	1.465×10^{-3}	0.997
26.16	13.53×10^{-2}	0.906	2.64×10^{-3}	3.078×10^{2}	2.153×10^{-3}	0.999
49.10	12.30×10^{-2}	0.986	3.74×10^{-3}	2.486×10^{2}	3.476×10^{-3}	0.997
103.80	12.25×10^{-2}	0.985	6.66×10^{-3}	1.407×10^{2}	6.243×10^{-3}	0.997

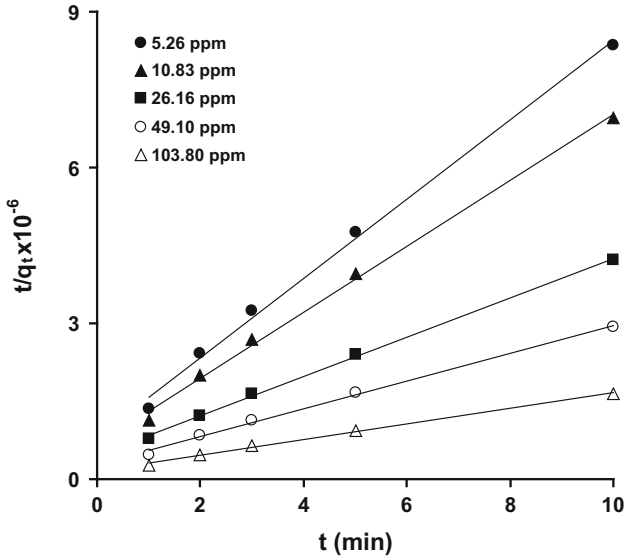


Fig. 8 The fitting of adsorption data on the pseudo-second order kinetic equation for the Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid at 293 K. The initial Sr(II) concentrations are 5.26 ppm (*filled circle*), 10.83 ppm (*filled triangle*), 26.16 ppm (*filled square*) 49.10 ppm (*open circle*) and 103.80 ppm (*open triangle*) at 293 K

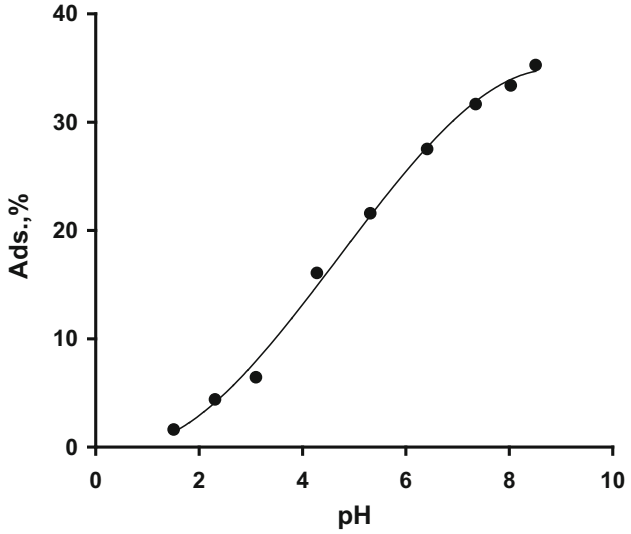


Fig. 9 The effect of the solution pH on the adsorption percentage of Sr(II). The Initial pH of 10.83 ppm of Sr(II) solution is 4.48. The amount of adsorbent is 5 mg. Other adsorption parameters of temperature (T) and contact time (t) are kept constants as $T = 293$ K and $t = 60$ min

resin has occurred by chemisorption mechanism [9, 32, 33, 50]. When we compare the values of adsorption rate constants (k), initial adsorption rates (h) and equilibrium adsorption capacity (q_e) as function of initial Sr(II) concentration at 293 K and at constant adsorbent mass ($m = 0.05$ g), With increasing the initial Sr(II) concentration from 5.26 to 103.80 ppm, the equilibrium adsorption capacity (q_e) and initial adsorption rates (h) increased from 1.31×10^{-3} mmol/g copolymer to 6.66×10^{-3} mmol Sr(II)/g copolymer and from 1.223×10^{-3} mmol Sr(II)/(g copolymer $\times$ min) to 6.243×10^{-3} mmol Sr(II)/(g copolymer $\times$ min), whereas the adsorption rate constants decreased from 7.123×10^{2} g copolymer/(mmol Sr(II) $\times$ min) to 1.407×10^{2} g copolymer/(mmol Sr(II) $\times$ min), respectively. The values of correlation coefficients indicated that the kinetic data obtained from experimental Sr(II) adsorption results fitted better to the pseudo-second order kinetic model than other kinetic models.

The effect of pH

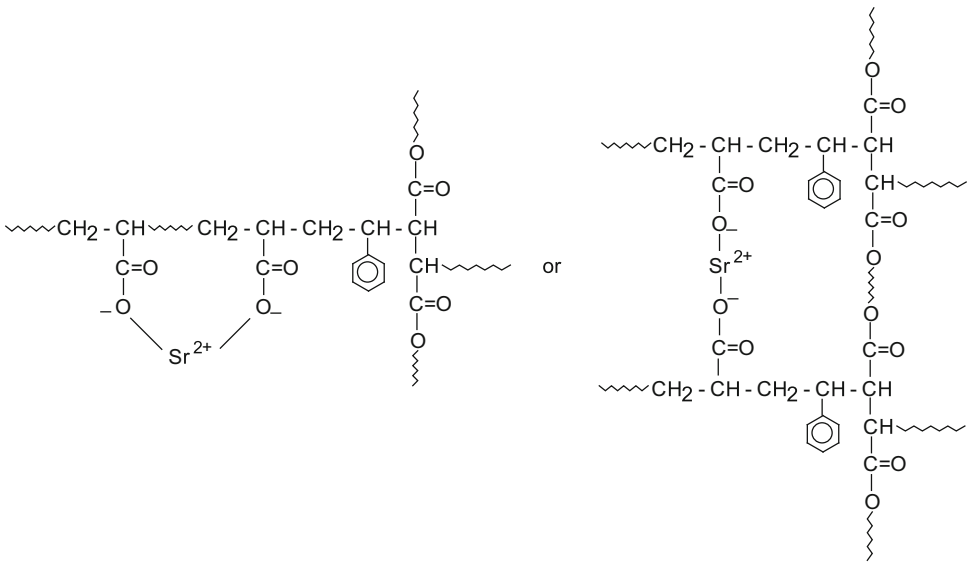
It is known that the pH of medium has an influence upon the adsorption of metal ions onto adsorbent [9, 32–34, 44, 50, 59–63]. In order to examine the dependence of Sr(II) adsorption on the crosslinked polyester resin, 5 mL of 10.83 ppm Sr(II) solutions at pH 4.48 and 0.05 g of adsorbent were mixed. The pH values of mixtures were adjusted by adding 0.01 M HCl and 0.01 M NaOH solutions. The pH value of prepared mixture of 5 mL Sr(II) and 0.05 g of the crosslinked polyester resin were varied from 1.5 to 8.5 keeping other parameters constants as adsorption temperature ($T = 293$ K) and contact time ($t = 60$ min) The effect of pH on the adsorption percentage of Sr(II) was illustrated in Fig. 9. As can be seen from Fig. 9, the adsorption percentage of the Sr(II) adsorbed on the crosslinked polyester resin first started to increase to 1.61 % at pH 1.5 and showed a marked increase from 6.44 to 31.66 %, with increasing pH from 3.1 to 7.35 and then reached an equilibrium value (33.38 %) at pH 8. The binding mechanism of Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid can be depicted in Scheme 2.

Regeneration and reuse at suitable pH value of the crosslinked polyester resin functionalized with acrylic acid can be easily performed with 0.1 M HCl and 0.1 M NaOH. Reusability of the selected crosslinked polyester resin was checked and it was found that for three consecutive runs there was no loss of adsorption capacity. These properties make the crosslinked polyester resin functionalized with acrylic acid potential candidate adsorbent for removal of radioactive or heavy metal ions from aqueous waste solutions.

The Effect of initial Sr(II) concentration

The dependence of the percentage and the amount of Sr(II) adsorption on the crosslinked polyester resin containing acrylic acid functional groups was investigated at different temperatures of $T = 283$, 293, 303 and 313 K at a constant time of $t = 60$ min (Fig. 10). As can be seen from Fig. 10,

Scheme 2 Chemical structure of Sr(II) binding mechanism of the crosslinked polyester resin functionalized with acrylic acid



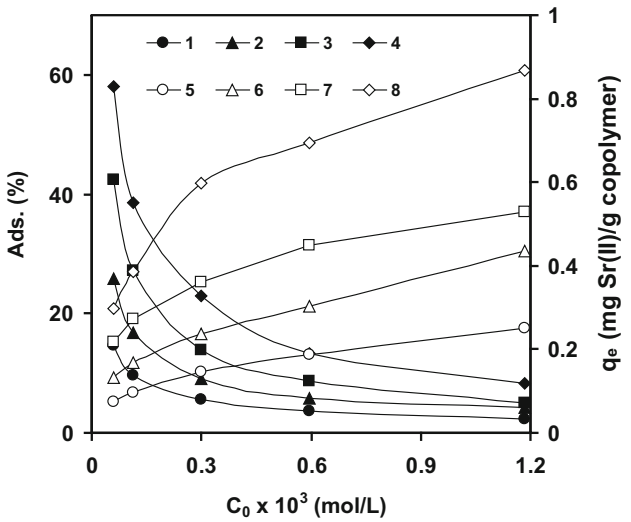


Fig. 10 The effect of initial Sr(II) concentration ranging from 5.13 to 103.90 ppm on the percentage (curves 1–4) and amount (curves 5–8) of adsorbed Sr(II) on the crosslinked polyester resin functionalized with acrylic acid at different temperatures of $T = 283$ K (*filled circle*), 293 K (*filled triangle*), 303 K (*filled square*) and 313 K (*filled diamond*) for the values of adsorption percentage (curves 1–4) of Sr(II) and $T = 283$ K (*open circle*), 293 K (*open triangle*), 303 K (*open square*) and 313 K (*open diamond*) for the values of amount (curves 5–8) of adsorbed Sr(II) at constant adsorption time ($t = 60$ min)

the percentage of strontium ions adsorbed on the crosslinked polyester resin decreased with increasing the initial Sr(II) concentration (Fig. 10, curves 1–4). However the amount of adsorbed Sr(II) increased with a rise in initial Sr(II) concentration (Fig. 10, curves 5–8). It was observed that when temperature in the adsorption measurements increased from 283 to 313 K, the percentage and amount of adsorbed Sr(II) on the crosslinked polyester resin increased from 14.74 to 58.03 % and from 7.56×10^{-2} mg Sr(II)/g copolymer to 29.76×10^{-2} mg Sr(II)/g copolymer

Table 3 The dependence of percentage and equilibrium adsorption capacity on the initial Sr(II) concentration ranging from 5.13 ppm to 103.90 ppm at different temperatures ($T = 283$, 293, 303 and 313 K) for Sr(II) adorption on the crosslinked polyester resin bearing acrylic acid functional groups from aqueous solutions

T (K)	C_0 (ppm)	Ads. (%)	q_e (mg Sr(II)/g copolymer)
283	5.13	14.74	7.56×10^{-2}
	9.99	9.56	9.56×10^{-2}
	26.08	5.64	14.70×10^{-2}
	52.12	3.59	18.70×10^{-2}
	103.90	2.41	25.00×10^{-2}
293	5.13	25.91	13.29×10^{-2}
	9.99	16.76	16.74×10^{-2}
	26.08	9.05	23.60×10^{-2}
	52.12	5.83	30.40×10^{-2}
	103.90	4.18	43.40×10^{-2}
303	5.13	42.39	21.74×10^{-2}
	9.99	27.21	27.19×10^{-2}
	26.08	13.80	36.00×10^{-2}
	52.12	8.63	45.00×10^{-2}
	103.90	5.09	52.90×10^{-2}
313	5.13	58.03	29.76×10^{-2}
	9.99	38.63	38.60×10^{-2}
	26.08	22.97	59.90×10^{-2}
	52.12	13.33	69.50×10^{-2}
	103.90	8.36	86.90×10^{-2}

respectively for 5.13 ppm Sr(II) concentration and from 2.41 to 8.36 % and 25.00×10^{-2} mg Sr(II)/g copolymer to 86.90×10^{-2} mg Sr(II)/g copolymer for 103.90 ppm Sr(II) concentration, respectively (Table 3) due to augmentation of the diffussibility of strontium ions on the

polymer matrix or more ionization of carboxyl groups by increase in temperature described in previous studies [9, 11, 25, 32].

The adsorption isotherms

The equilibrium relationship between concentration in the liquid phase and the concentration in the adsorbent particles at constant temperature and pH has been studied by adsorption isotherms such as the Freundlich, Langmuir and Duninin–Radushkevich (D–R) as defined in the literature [9, 32, 33, 43–48]. The fitting of adsorption data to the Freundlich, Langmuir and D–R isotherms was examined for initial Sr(II) concentrations ranging from 5.13 to 103.90 ppm at various temperatures ($T = 283$, 293, 303 and 313 K) at constant adsorption time ($t = 60$ min).

The Freundlich equation which is a suitable model for describing the surface heterogeneity, exponential distribution of active sites and infinite surface coverage has been written as follows:

$$q_e = K_F \times C_e^{n_F}, \quad (15)$$

where q_e is the amount of Sr(II) adsorbed on the crosslinked copolymer functionalized with acrylic acid from aqueous solution at equilibrium (mol/g) and C_e is the equilibrium solution concentration as mol/L. n_F and K_F are the Freundlich adsorption constants which relates adsorption intensity and adsorption capacity. The linearized form of equation has been presented as follows:

$$\log q_e = \log K_F + n_F \times \log C_e. \quad (16)$$

The plot of log q_e against log C_e plots shows a straight line in the linearized Freundlich Eq. (16) for the Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid as chelating agent at various temperatures ($T = 283$, 293, 303 and 313 K) and various initial Sr(II) concentrations of $C_{Sr(II)} = 5.13$, 9.99, 26.08, 52.12 and 103.90 ppm (Fig. 11). The n_F and K_F constants in the Freundlich equation were calculated from the values of slope and intercept of the lines for the range of initial Sr(II) concentrations from 5.13 to 103.90 ppm at various temperatures at a constant contact time of $t = 60$ min were listed in Table 4. As seen from Table 4, the n_F values were found as $0.257 \leq n_F \leq 0.383$ for temperature range from 283 to 313 K. The correlation coefficient for the Freundlich plot was found to be of $0.990 \leq R \leq 0.999$. These results indicated that heterogeneous adsorption of Sr(II) on the crosslinked polyester resin functionalized with acrylic acid from aqueous solutions occurred and n values meant that adsorption surface was heterogeneous as described in previous investigations [9, 11, 32, 33, 63, 64].

Fitting of adsorption data on the Langmuir adsorption isotherm was examined for Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid from aqueous solutions and the following linearized forms of Langmuir I (Eq. 17) and II (Eq. 18) equations were used to describe equilibrium data:

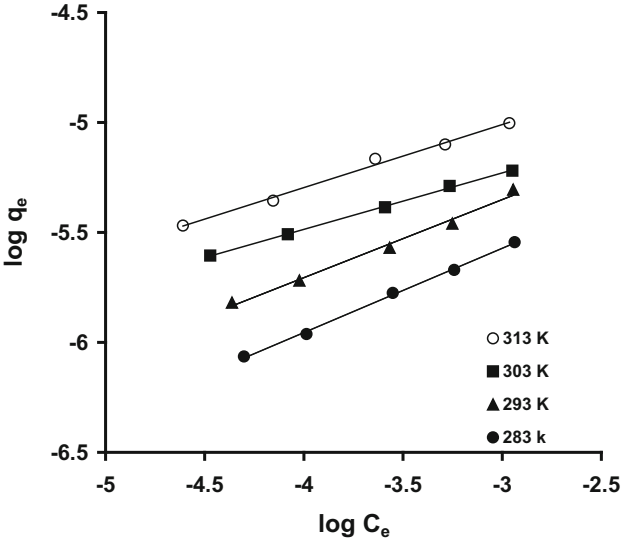


Fig. 11 The relation between log q_e against log C_e for the Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid for various initial Sr(II) concentrations at constant temperature of 293 K and time of $t = 60$ min

Table 4 The n_F and K_F values determined at different temperatures ($T = 283$, 293, 303 and 313 K) by applying the Freundlich adsorption isotherm to the adsorption data

T (K)	n_F	K_F	R
283	0.383	3.785×10^{-5}	0.998
293	0.355	5.174×10^{-5}	0.990
303	0.257	3.467×10^{-5}	0.999
313	0.287	7.094×10^{-5}	0.992

$$\frac{C_e}{q_e} = \frac{1}{bq_m} + \frac{C_e}{q_m} \quad (17)$$

$$\frac{1}{q_e} = \frac{1}{bq_m C_e} + \frac{1}{q_m}, \quad (18)$$

where q_e is the amount of Sr(II) adsorbed on the crosslinked copolymer bearing acrylic acid functional groups at equilibrium (mol/g), C_e is the equilibrium solution concentration as mol/L, the q_e and b are the Langmuir adsorption capacity and adsorption constant respectively. Figures 12 and 13 shows the plot of C_e/q_e versus C_e and $1/q_e$ versus $1/C_e$ indicating the relationships between the C_e/q_e and C_e values and between $1/q_e$ and $1/C_e$ values have been not linear, implying that the adsorption data did not show a good fit to the Langmuir I and II equations respectively. The correlation coefficients, and the values of q_m and b are listed in Table 5. As seen from Table 5, the

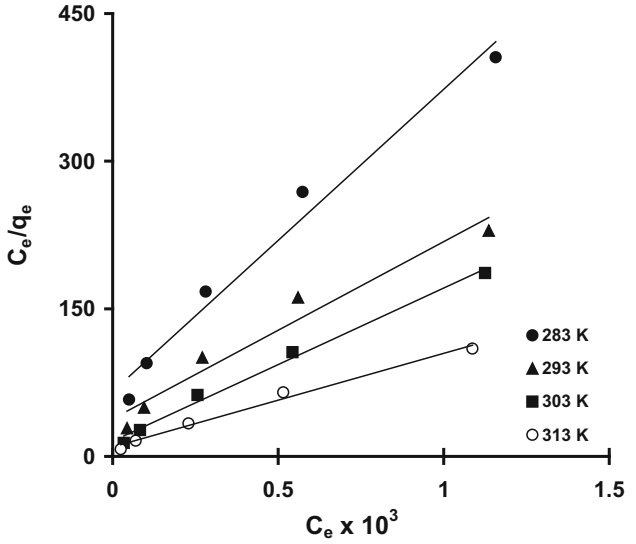


Fig. 12 The application of adsorption data on the linearized Langmuir equation I for initial Sr(II) concentration changing from 5 13 to 103.90 ppm at different temperatures of $T = 283$ K (*filled circle*), 293 K (*filled triangle*), 303 K (*filled square*) and 313 K (*open circle*) and at constant adsorption time of $t = 60$ min

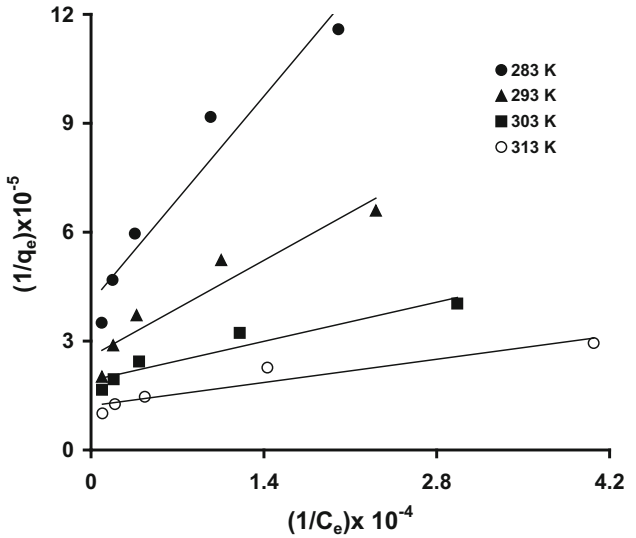


Fig. 13 The application of adsorption data on the linearized Langmuir equation II for initial Sr(II) concentration changing from 5 13 to 103.90 ppm at different temperatures of $T = 283$ K (*filled circle*), 293 K (*filled triangle*), 303 K (*filled square*) and 313 K (*open circle*) and at constant adsorption time of $t = 60$ min

correlation coefficients are found to be in the ranges of $0.956 \leq R \leq 0.992$ and $0.905 \leq R \leq 0.937$ for the Langmuir equations I and II respectively at temperature range from 283 to 313 K at constant adsorption time ($t = 60$ min). The deviation from linearity for fitting of adsorption data to the Langmuir isotherm could be due to the fact that these types of isotherms have originally been derived for the adsorption of gases on the adsorption surfaces and thus have been some limitations in the extrapolation of adsorption of other compounds [25, 32, 33, 65, 66] as in current study.

The D–R isotherm model has been applicable at low concentration range and could be used to describe the sorption on both homogeneous and heterogeneous surfaces [67–70]. The D–R isotherm model was represented by the following equation:

$$q_{\mathrm{e}} = q_m \exp -\left(K\varepsilon^2\right), \tag{19}$$

where ε is the polany potential given as $RT \ln(1 + 1/C_{\mathrm{e}})$(kJ/mol), R is the ideal gas constant (8.314 J/mol K), T is absolute temperature (K) and q_m is adsorption capacity per unit weight (mol/g). K is the D–R isotherm constant in the term of ($\mathrm{mol}^2/\mathrm{kJ}^2$) related to the degree of adsorbate adsorption by adsorbent surface Linearized form of D–R equation was

$$\ln q_{\mathrm{e}} = \ln q_{\mathrm{m}} - K\varepsilon^2. \tag{20}$$

The values of K and q_m obtained from the slope and intercept of straight lines are ilustrated in Fig. 14 at different adsorption temperatures. The correlation coefficient (R) of straight lines was found to be in the range of $0.972 \leq R \leq 0.997$. The K and q_m values in the linearized D–R equation at different adsorption temperatures were found as -3.7×10^{-3} and 7.834×10^{-3} mmol Sr(II)/g copolymer at 283 K, -3.4×10^{-3} and 11.805×10^{-3} mmol Sr(II)/g copolymer at 293 K, -2.4×10^{-3} and 11.805×10^{-3} mmol Sr(II)l/g copolymer at 303 K and -2.7×10^{-3} and 20.874×10^{-3} mmol Sr(II)/g copolymer at 313 K respectively (Table 6). The apparent free energy of adsorption (E, kJ/mol) which is the energy change when 1 mol of ion is transferred to the surface of solid from infinity in the solution was calculated using the following relationship [9, 25, 32, 33, 67–70]:

$$E = (-2K)^{-1/2}. \tag{21}$$

The E values for the Sr(II) adsorption on the crosslinked polyester resin bearing acrylic acid functional groups from aqueous solutions at different temperatures of $T = 283$, 293, 303 and 313 K were found as 11.62, 12.13, 14.43 and 13.61 kJ/mol, respectively by using Eq. (21) [9, 25, 32, 33, 67–70]. It was reported in previous investigations [9, 25, 32, 33, 67–70], the adsorption energy could be employed to estimate the type of adsorption based on ion-exchange mechanism which is around 8–16 kJ/mol. The average adsorption energy, E which was found as 12.95 kJ/mol determined in present study was in the energy ranges of ion-exchange described above. Therefore, the Sr(II) adsorption by crosslinked polyester resin functionalized with acrylic acid has been of ion-exchange.

Table 5 The adsorption capacity (q_m) and b values determined at different temperatures ($T = 283$, 293, 303 and 313 K) by applying the linearized forms (Eqs. I and II) of Langmuir isotherm to the adsorption data

T (K)	Linearized Langmuir I equation			Linearized Langmuir II equation		
	q_m (mmol/g)	b (L/mmol)	R	q_m (mmol/g)	b (L/mmol)	R
283	3.256×10^{-3}	4.661	0.978	2.453×10^{-3}	10.071	0.937
293	5.557×10^{-3}	4.715	0.956	3.879×10^{-3}	13.641	0.905
303	6.431×10^{-3}	10.038	0.992	5.226×10^{-3}	24.852	0.910
313	10.520×10^{-3}	9.858	0.989	8.190×10^{-3}	26.740	0.905

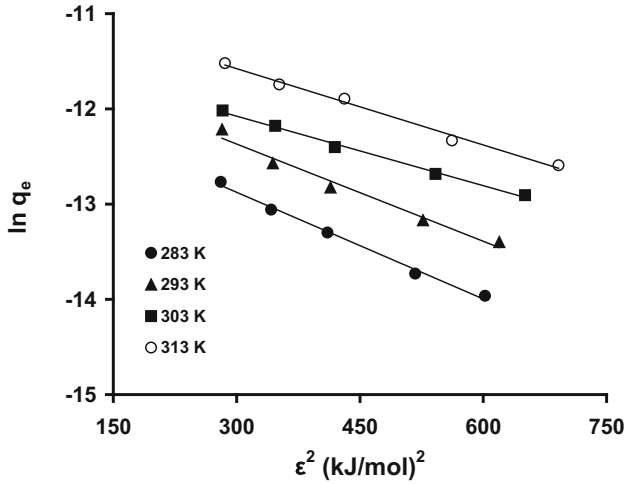


Fig. 14 The fitting of adsorption data on the D–R isotherm for adsorption on the crosslinked polyester resin functionalized with acrylic acid at different temperatures of $T = 283$ K (*filled circle*), 293 K (*filled triangle*), 303 K (*filled square*) and 313 K (*open circle*) and at constant adsorption time of $t = 60$ min

The effect of temperature

The increase in the temperature has generally increased the adsorption of metal ions on adsorbent surfaces bearing carboxylate functional groups due to increase in mobility of ionic species in solution and acceleration of some originally slow steps at higher temperature reported in previous studies [9, 25, 32]. The dependence of Sr(II adsorption on the temperature ranging from 283 to 313 K for Sr(II) adsorption by crosslinked polyester resin functionalized with acrylic acid from aqueous solutions were examined for various Sr(II) concentration from 5.13 to 26.08 ppm (Fig. 15). As can be seen from Fig. 15, when the temperature of adsorption increased from 283 to 313 K, the percentage of Sr(II) adsorbed on the crosslinked copolymer increased.

In order to determine the thermodynamic parameters for Sr(II) adsorption reaction by crosslinked polyester resin, the following equation was used to calculate $\Delta H°$ and $\Delta S°$ values

$$\ln K_D = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT}, \tag{22}$$

where K_D is the constant of distribution coefficient (cm^3/g), $\Delta S°$ is the standard entropy (kJ/(mol K), $\Delta H°$ is the standard enthalpy (kJ/mol), T is the absolute temperature (K) and R is the gas constant ($R = 8.314 \times 10^{-3}$ kJ/mol K). The relationship between ln K_D and $1/T$ values for various initial Sr(II) concentration from 5.13 to 26.08 ppm was illustrated in Fig. 16. Entropy and enthalpy values for Sr(II) adsorption on the crosslinked copolymer were calculated from the intercept and slope of Eq. (22) given above. The standard free energy values were determined by using the following equatin given below.

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ, \tag{23}$$

where $\Delta G°$ is the standard free energy (kJ/mol). The calculated results of $\Delta H°$, $\Delta S°$ and $\Delta G°$ values were listed in Table 7. The positive values of enthalpy ($\Delta H°$) correspond to the endothermic adsorption process. The value of free energy ($\Delta G°$) are negative and indicate that a decrease in $\Delta G°$ values with increase in temperature and initial Sr(II) concentration. Positive entropy ($\Delta S°$) reflects the affinity of crosslinked polyester resin and the contribution of entropic term makes the adsorption free energy negative as described in earlier studies [9, 32, 50, 55, 68].

Table 6 The values of correlation coefficient (R), K, and q_m and E obtained by applying D–R isotherm to the adsorption data at different temperatures

T (K)	q_m (mmol Sr(II)/g resin)	$-K$ (mol^2/kJ^2)	R	E (kJ/mol)
283	7.834×10^{-3}	3.7×10^{-3}	0.994	11.64
293	11.805×10^{-3}	3.4×10^{-3}	0.977	12.13
303	11.805×10^{-3}	2.4×10^{-3}	0.995	14.43
313	20.874×10^{-3}	2.7×10^{-3}	0.992	13.61

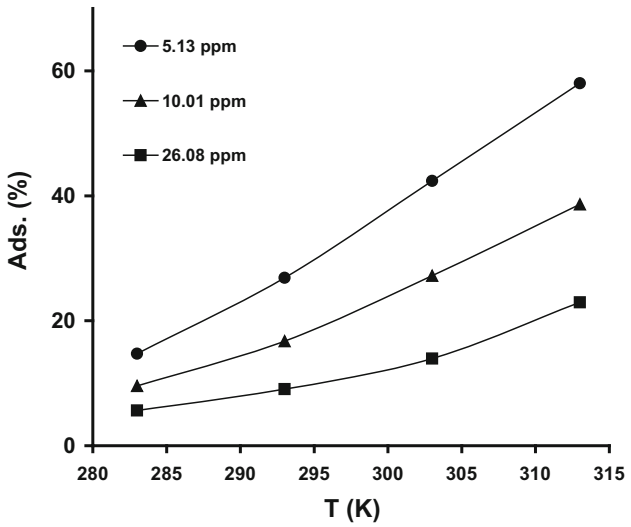


Fig. 15 The dependence of adsorption percentage on the temperature for the Sr(II) adsorption on the crosslinked polyester resin bearing acrylic acid functional groups from aqueous solution. Initial Sr(II) concentrations are 5.13 ppm (*filled circle*), 10.01 ppm (*filled triangle*) and 26.08 ppm (*filled square*) at constant adsorption time of $t = 60$ min and the pH (the pH of initial Sr(II) solutions is around 4.48)

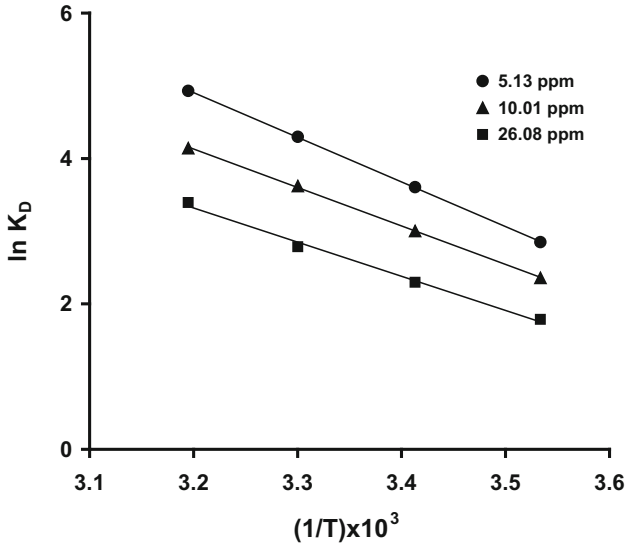


Fig. 16 The plot of ln K_D versus $1/T$ for the Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid at different initial Sr(II) concentration of 5.13 ppm (*filled circle*), 10.01 ppm (*filled triangle*) and 26.08 ppm (*filled square*) at constant adsorption time of $t = 60$ min

Conclusion

The crosslinked copolymer obtained from the mixture of unsaturated polyester resin dissolved in styrene and acrylic acid was used for Sr(II) adsorption from aqueous solutions. The dependence of Sr(II) adsorption on the amount of adsorbent, contact time, pH of solution and temperature was investigated. With increasing the amount of adsorbent from 0.01 to 0.07 g in the adsorption measurements of Sr(II) at 293 K, it was observed that the adsorption percentage increased and reached an equilibrium at the range of $m_{\text{Copolymer}} = 0.05$–$0.07$ g. The fitting of adsorption data obtained from experimental results produced as depending on contact time was analyzed by the modified Freundlich, the Elovich, the pseudo-first order and the pseudo-second order kinetic models. It was observed that the adsorption data obtained as depending on contact time provided much better fitting for the pseudo-second order kinetic equation with high correlation coefficients ($0.997 \leq R \leq 0.999$). The goodness of the fit of adsorption data to the pseudo-second order kinetic model indicates that Sr(II) adsorption on the crosslinked polyester resin bearing acrylic acid functional groups occurred by chemisorption mechanism. When the pseudo second order kinetic model was applied to the obtained experimental results depending on contact time, it was observed that with increasing the initial Sr(II) concentration from 5.26 to 103.80 ppm, the equilibrium adsorption capacity(q_e) and initial adsorption rates (h) increased from 1.31×10^{-3} mmol/g copolymer to 6.66×10^{-3} mmol Sr(II)/g copolymer and from 1.223×10^{-3} mmol Sr(II)/(g copolymer x min) to 6.243×10^{-3} mmol Sr(II)/(g copolymer $\times$ min), whereas the adsorption rate constants decreased from 7.123×10^2 g copolymer/(mmol Sr(II) $\times$ min) to 1.407×10^2 g copolymer/(mmol Sr(II) $\times$ min), respectively. When the dependence of adsorption percentage of Sr(II) on the pH of solution was examined, It was observed that the adsorption percentage of Sr(II) adsorbed on the crosslinked polyester resin indicated a marked influence from 6.44 to 31.66 %, with increasing pH of solution from 3.1 to 7.35 and then reached an equilibrium value (33.38 %) at pH 8. Regeneration and use at suitable pH value of the crosslinked polyester resin functionalized with acrylic acid can be easily performed with 0.1 M HCl and 0.1 M NaOH. Reusability of the selected crosslinked polyester resin was checked and it was found that for three consecutive runs there was no loss of adsorption capacity. These properties make the crosslinked polyester resin functionalized with acrylic acid potential candidate adsorbent for removal of radioactive or heavy metal ions from aqueous waste solutions. When the effect of initial Sr(II) concentration on the Sr(II) adsorption by the crosslinked copolymer functionalized with acrylic acid was examined, with increasing the initial Sr(II) concentration from 5.13 to 103.90 ppm at different temperatures of 283, 293, 303 and 313 K and at constant contact time of 60 min, the percentage of Sr(II) adsorbed on 0.05 g of adsorbent decreased. Whereas the amount of adsorbed Sr(II) increased. It was also observed that adsorption temperature increased from 283 to 313 K,

Table 7 The calculated values of thermodynamic parameters of enthalpy ($\Delta H°$), entropy ($\Delta S°$) and free energy change ($\Delta G°$) for the adsorption of Sr(II) on the crosslinked polyester resin functionalized with acrylic acid from aqueous solutions

$C°$ (ppm)	$\Delta H°$ (kJ/mol)	$\Delta S°$ (kJ/mol K)	$-\Delta G°$ (kJ/mol)				R
			283 K	293 K	303 K	313 K	
5.13	51.07	20.42×10^{-2}	6.75	8.79	10.84	12.88	0.999
10.01	44.02	17.52×10^{-2}	5.39	7.34	9.09	10.85	0.999
26.08	39.03	15.26×10^{-2}	4.17	5.69	7.22	8.74	0.994

All the values except for C_0 were obtained by average of three measurements with ±0–3 % errors

the percentage and amount of adsorbed Sr(II) on the crosslinked polyester resin increased from 14.74 to 58.03 % and from $7.56 \times 10^{-2} \times$ mg Sr(II)/g copolymer to 29.76×10^{-2} mg Sr(II)/g copolymer for 5.13 ppm of the initial Sr(II) concentration and from 2.41 to 8.36 % and from 25.00×10^{-2} mg Sr(II)/g copolymer to 86.90×10^{-2} mg Sr(II)/g copolymer for 103.90 ppm of the initial Sr(II) concentration, respectively at constant contact time of 60 min. The produced adsorption data depending on the initial Sr(II) concentration were examined by the Freundlich, Langmuir and D–R isotherms at different temperatures of 283, 293, 303 and 313 K. The n_F values determined from the Freundlich equation at different temperatures were found to be $0.257 \leq n_F \leq 0.383$ Average free energy change and adsorption capacities by using adsorption data depending for various initial Sr(II) concentrations and temperatures were calculated as 12.95 kJ/mol and 13.08×10^{-3} mmol Sr(II)/g copolymer, respectively. It was reported that an energy adsorption based on ion exchange mechanism was around 8–16 kJ/mol. The adsorption free energy of 12.95 kJ/mol determined in this study was in the range of ion-exchange energy. Therefore the Sr(II) adsorption by the crosslinked polyester resin functionalized with acrylic acid has been ion-exchange type. By using adsorption data obtained at various temperatures and initial Sr(II) concentrations of 5.13, 10.01 and 26.08 ppm, enthalpy ($\Delta H°$), entropy ($\Delta S°$) and free energy change ($\Delta G°$) were calculated for Sr(II) adsorption on the crosslinked polyester resin functionalized with acrylic acid from aqueous solutions. The enthalpy value ($\Delta H°$) found in this study found to be positive shows the nature endothermic adsorption process. The value of free energy ($\Delta G°$) has been negative and indicates a decrease in $\Delta G°$ values with increase in temperature. Positive entropy ($\Delta S°$) found in the Sr(II) adsorption experiments reflects the affinity of the crosslinked polyester resin bearing acrylic acid functional groups as adsorbent towards strontium ions in the Sr(II) solutions and consequently contribution of entropy term makes the free energy change negative.

References

1. Oleksiienko O, Levchuk I, Sitarz M, Meleshevych S, Strelko V, Sillanpää M (2015) Removal of strontium (Sr^{2+}) from aqueous solutions with titanosilicates obtained by the sol–gel method. J Colloid Interf Sci 438:159–168
2. Zhou LM, Jia YY, Peng J, Liu ZR, Al-Zaini E (2014) Competitive adsorption of uranium(VI) and thorium(IV) ions from aqueous solution using triphosphate-crosslinked magnetic chitosan resins. J Radioanal Nucl Chem 302(1):331–340
3. Zavodska L, Kosorinova E, Scerbakova L, Lesny J (2008) Enviromental chemistry of uranium. HV ISSN 1418-7108: HEJ Manuscript No: ENV-081221-A, pp 1–18
4. Hassan HS, Atallah MF, Yakout SM (2010) Sorption characteristics of an economical sorbent material used for removal radioisotopes of cesium and europium. J Radioanal Nucl Chem 286:17–26
5. Mishra SP, Tiwari D (2002) Inorganic ion exchanger in radioactive waste management. Part XII Removal behavior of stannic and zirconium phosphate for strontium. J Radioanal Nucl Chem 352(3):421–426
6. Rao TP, Metilda P, Gladis JM (2006) Preconcentration techniques for uranium(VI) and thorium(IV) prior to analytical determination-an overview. Talanta 68:1047–1064
7. Yıldız B, Erten HN, Kış M (2011) The sorption behavior of Cs^+ ion on clay minerals and zeolite in radioactive waste management: sorption kinetics and thermodynamics. J Radioanal Nucl Chem 288:475–483
8. Chen J-P (1997) Batch and continous adsorption of strontium by plant root tissues. Bioresour Technol 60:185–189
9. Özeroglu C, Metin M (2012) Adsorption of uranium ions by crosslinked polyester resin functionalized with acrylic acid from aqueous solutions. J Radioanal Nucl Chem 292:923–935
10. Zhang Z, Xu X, Yan Y (2010) Kinetic and thermodynamic analysis of selective adsorption of Cs(I) by a novel surface whisher-supported ion-imprinted polymer. Desalination 263:97–106
11. Özeroğlu C, Keçeli G (2007) Kinetics of adsorption of strontium ions by a crosslinked copolymer containing methacrylic acid functional groups. Radiochim Acta 95:459–466
12. Lu NP, Mason CFV (2001) Sorption-desorption behavior of ^{85}Sr onto montmorillonite and silica colloids. Appl Geochem 16:1653–1662
13. Mckinley JP, Zachara JM, Smith SC, Liu C (2007) Cation exchange reactions controlling desorption of $^{90}Sr^{2+}$ from coarse-grained contaminated sediments at the Hanford site, Washington. Geochim Cosmochim Ac 71:305–325
14. Liu Q, Liu HN, Liu TY, Guo M, Qing BJ, Ye XS, Wu ZJ (2010) Strontium and calcium ion adsorption by molecularly imprinted hybrid gel. Chem Eng J 157(2–3):401–407

15. Kaçan E, Kütahyalı C (2012) Adsorption of strontium from aqueous solution using activated carbon produced from textile sewage sludges. J Anal Appl Pyrol 97:149–157
16. Rosskopfová O, Galamboš M, Rajee P (2011) Study of sorption processes of strontium on the synthetic hidroxyapatite. J Radioanal Nucl Chem 287:715–722
17. Galamboš M, Kufčáková J, Rosskopfová O, Rajee P (2010) Adsorption of cesium and strontium on natrified bentonites. J Radioanal Nucl Chem 283:803–813
18. Mohapatra PK, Manchanda VK (1998) Ion-pair extraction of uranyl ion from aqueous medium using crown ethers. Talanta 47(5):1271–1278
19. Agrawal YK, Shrvastav P, Menon SK (2000) Solvent extraction of U(VI) with crown ether. Sep Purif Technol 20(2–3):177–183
20. El-Shahat MF, Moawed EA, Faray AB (2007) Chemical enrichment and separation of uranyl ions in aqueous media using novel polyurethane foam chemically grafted with different basic dyestuff sorbents. Talanta 71(1):236–241
21. Prameuro E, Prevot AB, Zelano V, Galmini M, Vicardi G (1996) Selective recovery of uranium(VI) from aqueous acid solutions using miceller ultrafiltration. Analyst 121(10):1401–1405
22. Kim JH, Lee HI, Yeon J-W, Jung Y, Kim JM (2010) Removal of uranium(VI) from aqueous solutions by nanoporous carbon and its chelating polymer composite. J Radioanal Nucl Chem 286:129–133
23. Sivaiah MV, Venkatesan KA, Krishna RM, Sasidhar P, Murthy GS (2005) Ion exchange properties of strontium on in situ precipitated polyantimonic acid in amberlite XAD-7. Sep Purif Technol 44:1–9
24. Pekel N, Güven O (2003) Seperation of uranyl ions with amideoximated polyacrylonitrile/*N*-vinylimidazole complexing sorbents. Colloids Surf A 212:155–161
25. Özeroğlu C, Keçeli G (2006) Removal of strontium ions by a crosslinked copolymer containing methacrylic acid functional groups. J Radioanal Nucl Chem 268(2):211–219
26. Denizli A, Say R, Garipcan B, Patır S (2004) Methacryloylamido glutamic acid functionalized poly(2-hydroxyethyl methacrylate) beads for UO_2^{2+} removal. React Funct Polym 58:123–130
27. Badawy SM, Sokker HH, Othman SH, Hashem A (2005) Cloth filter for recovery of uranium from radioactive waste. Radiat Phys Chem 73:125–130
28. Nogami M, Sugiyama Y, Kawasaki T, Harada M, Morita Y, Kikuchi T, Ikeda Y (2010) Adsorptivity of polyvinylpyrrolidone for selective separation of U(VI) from nitric acid media. J Radioanal Nucl Chem 283:541–546
29. Choi S-H, Nho YC (2000) Adsorption of UO_2^{2+} by polyethylene adsorbents with amidoxime, carboxyl and amidoxime/carboxyl group. Radiat Phys Chem 57:187–193
30. Badawy SM (2003) Uranium isotope enrichment by complexation with chelating polymer adsorbent. Radiat Phys Chem 66:67–71
31. Saraydın D, Işıkver Y, Şahiner N (2001) Uranyl ion binding properties of poly(hydroxamic acid) hydrogels. Polym Bull 47:81–89
32. Özeroğlu C, Doğan E, Keçeli G (2011) Investigation of Cs(I) adsorption on densely crosslinked poly(sodium methacrylate) from aqueous solutions. J Radioanal Nucl Chem 289(2):577–586
33. Özeroğlu C, Keçeli G (2009) Kinetic and thermodynamic studies on the adsorption of U(VI) ions on densely crosslinked poly(-methacrylic acid) from aqueous solutions. Radiochim Acta 97:709–717
34. Venkatesan KA, Shymala KV, Antony MP, Srinivasan TG, Rao PRV (2008) Batch and dynamic extraction of uranium(VI) from nitric acid medium by commerical phoshinic acid resin, Tulsion ^{96}Ch. J Radioanal Nucl Chem 275(3):563–570
35. Karadağ E, Saraydın D, Güven O (1995) Behaviors of acrylamide itaconic acid hydrogels in uptake of uranyl ions from aqueous solutions. Sep Sci Technol 30:3747–3760
36. Metilda P, Sanghamitra K, Gladis JM, Naidu GRK, Rao TP (2005) Amberlite XAD-4 functionalized with succinic acid for a solid phase extractive preconcentration and separation of uranium(VI). Talanta 66:192–200
37. Biçak N, Şenkal BF, Yarbaş T (1998) Crosslinked poly(styrenesulfonamide) with iminoacetic acid chelating groups for hard-water treatment. Macromol Chem Phys 199:2731–2735
38. Bjorksten J, Tovey H, Harker B, Henning J (1956) Polyesters and their applications. Reinhold Publishing Corporation, New York
39. Sanchez EMS, Zavaglia CAC, Felisberti MI (2000) Unsaturated polyester resin: influence of the miscibility and mechanical properties. Polymer 41(2):765–769
40. Delahaye N, Marais S, Saiter JM, Metayer M (1998) Characterization of unsaturated polyester resin cured with styrene. J Appl Polym Sci 67:695–703
41. Özeroğlu C (2004) The effect of tertiary amines on free radical polymerization of unsaturated polyester and styrene. Polym Plast Technol 43(3):661–670
42. Storey RF, Sudhakar D, Hogue M (1986) Tertiary aromatic amines as curing reaction promoters for unsaturated polyester resin. 2. Low temperature studies. J Appl Polym Sci 32(5):4919–4930
43. Martin JL (1999) Kinetic analysis od an asymmetrical DSC peak in the curing of an unsaturated polyester resin catalyzed with MEKP and cobalt octoate. Polymer 40:3451–3462
44. Morsy AMA, Hussein AEM (2011) Adsorption of uranium from crude phosphoric acid using activated carbon. J Radioanal Nucl Chem 288:341–346
45. Mellah A, Chegroughe S, Barkat M (2006) The removal of uranium(VI) from aqueous solutions onto activated carbon: kinetic and thermodynamic investigations. J Colloid Interface Sci 296:434–441
46. Qadeer R, Hanif J (1994) Kinetics of uranium(VI) ions adsorption on activated charcoal from aqueous solutions. Radiochim Acta 65:259–263
47. Yavari R, Huang YD, Ahmadi SJ (2011) Adsorption of cesium(I) from aqueous solution using oxidized multiwall carbon nanotubes. J Radioanal Nucl Chem 287:393–401
48. Çelebi O, Kilikli A, Erten HN (2009) Sorption of radioactive cesium and barium ions onto solid humic acid. J Hazard Mater 168:695–703
49. Ho YS, McKay G (2002) Application of kinetic models on the sorption of copper(II) on to peat. Adsorpt Sci Technol 20(8):797–815
50. Kadous A, Didi MA, Villemin D (2011) Removal of uranium(VI) from actate medium using TP 260 resin. J Radioanal Nucl Chem 288:553–561
51. Liu Y, Liu Y, Cao X, Hua R, Wang Y, Pang C, Hua M, Li X (2011) Biosorption study of uranium(VI) on crosslinked chitosan: isotherm, kinetic and thermodynamic aspects. J Radioanal Nucl Chem 290:231–239
52. Lagergren S (1898) Zur theorie der sogenannten sdsorption gelöster dtoffe. Kungliga Svenska Vetenskapsakademiens, Handlingar 24(4):1–39
53. Ho YS (2004) Citation review of Lagergren kinetic rate equation on adsorption reactions. Scientometrics 59:171–177
54. Tan L, Jin Y, Chen J, Wu J, Feng L (2011) Sorption of Radiocobalt(II) from aqueous solutions to Na–attapulgite. J Radioanal Nucl Chem 289:601–610
55. Zhu W, Liu Z, Chen L, Dong Y (2011) Sorption of uranium(VI) on Na–attapulgite as a function of contact time, solid content, pH, ionic strength, temperature and humic acid. J Radioanal Nucl Chem 289:781–788

56. Ho YS, McKay G (2000) The kinetics of sorption of divalent metal ions onto sphagnum moss peat. Water Res 34(3):735–742
57. Fan F, Ding H, Bai J, Wu X, Lei F, Tion W, Wang Y, Qin Z (2011) Sorption of U(VI) from aqueous solution onto magnesium silicate hallow spheres. J Radioanal Nucl Chem 289:367–374
58. Ho YS (2006) Review of second-order models for adsorption systems. J Hazard Mater 136(3):681–689
59. Zhang A, Asakura T, Uchiyama G (2003) The adsorption mechanism of uranium(VI) from sea water on a macroporous fibrous polymeric adsorbent containing amidoxime chelating functional group. React Funct Polym 57:67–76
60. Bargar JR, Reitmeyer R, Lenhart JJ, Davis JA (2000) Characterization of U(VI)-carbonato ternary complexes on hematite: EXAFS and electrophoretic mobility measurements. Geochim Cosmochim Ac 64(16):2737–2749
61. Mishra SP, Tiwary D (1999) Ion exchangers in radioactive waste management. Part XI. Removal of barium and strontium ions from aqueous solutions by hydrous ferric oxide. Appl Radiat Isotopes 51:359–366
62. Papachristodoulou CA, Assimakopoulos PA, Gangas NHJ (2002) Strontium adsorption properties of an aluminum-pillared montmorillonite carrying carboxylate functional groups. J Colloid Interface Sci 245:32–39
63. Bagerifam S, Lakzian A, Ahmadi SJ, Ahmadi SJ, Rahimi MF, Halajnia A (2010) Uranium removal from aqueous solution by wood powder and wheat straw. J Radioanal Nucl Chem 283:289–296
64. Zhang Y, Zhao H, Fan Q, Zheng X, Li P, Luis S, Wu W (2011) Sorption of U(VI) onto a decarbonated calcareous soil. J Radioanal Nucl Chem 288:395–404
65. Escrig I, Morell I (1998) Effect of cadmium on soil adsorption of cadmium and zinc in some Spanish sandy soils. Water Air Soil Pollut 105:507–520
66. Sharwan T, Erten HN (2002) Thermodynamic parameters of Cs+ sorption on natural clay. J Radioanal Nucl Chem 253(1):115–120
67. Sari A, Tuzen M, Citak D, Soylak M (2007) Equilibrium, kinetic and thermodynamic studies of adsorption of Pb(II) from aqueous solution onto Turkish kaolinite clay. J Hazard Mater 149(2):283–291
68. Kundu S, Gupta AK (2006) Investigations on the adsorption efficiency of iron oxide coated cement (IOCC) towards As(V)-kinetics, equilibrium and thermodynamic studies. Colloid Surf A 273:121–128
69. Chen L, Gao B, Lu S, Dong Y (2011) Sorption study of radionicel on attapulgite as a function of pH, ionic strength and temperature. J Radioanal Nucl Chem 288:851–858
70. Wang M, Qiu J, Tao X, Wu C, Cui W, Lui Q, Lu S (2011) Effect of pH and ionic strength on U(VI) adsorption to oxidized multiwalled carbon nanotubes. J Radioanal Nucl Chem 288:895–901