Application of Scallop shell-Fe$_3$O$_4$ nanoparticles for the removal of Cr(VI) from aqueous solutions

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ABSTRACT

In this study, removal of Cr(VI) by Scallop shell-Fe$_3$O$_4$ nanoparticles was investigated with variation of pH, adsorbent dosage, initial Cr(VI) concentration, ionic strength and temperature. Coating of Fe$_3$O$_4$ nanoparticles onto Scallop shell was identified by Fourier transform infrared spectroscopy, X-ray diffraction, scanning electron microscopy and energy dispersive X-ray analysis. The maximum adsorption was observed at pH 3. Removal efficiency of Cr(VI) was increased with increasing adsorbent dosage, but was decreased with increasing initial Cr(VI) concentration and temperature. Removal efficiency of Cr(VI) was decreased in the presence of sulfate and carbonate ions. Adsorption kinetic study revealed that a pseudo-second order model better described the removal data than a pseudo-first order model and an intra-particle diffusion model. Maximum adsorption capacity was estimated to be 34.48 mg/g. Thermodynamic studies indicated that adsorption of Cr(VI) onto Scallop shell-Fe$_3$O$_4$ nanoparticles occurred via an exothermic ($\Delta H = -320.88$ KJ mol$^{-1}$) process. Adsorption efficiency of Cr(VI) by Scallop shell-Fe$_3$O$_4$ nanoparticles was maintained even after eight successive cycles.

Key words | adsorption, Cr(VI), kinetic and isotherm models, Scallop shell-Fe$_3$O$_4$, thermodynamics

INTRODUCTION

Chromium generally contaminates in aquatic systems through discharge of concentrated effluents mainly from leather tanning, smelting, electroplating, paint, textile and paper industries (Liu et al. 2015). It is generally known that chromium exists in the aquatic environment mainly in two oxidation states: Cr(VI) and Cr(III) (Margiotta et al. 2012; Dermatas et al. 2015; Khitous et al. 2015). The presence of high concentrations of Cr(VI) in aquatic environment such as groundwater and spring water was mainly attributed to anthropogenic activities (Margiotta et al. 2012; Dermatas et al. 2015; Khitous et al. 2015). Cr(VI) is more toxic and mobile than Cr(III) (Khitous et al. 2015). Thus, Cr(VI) contamination in aquatic environment is a great concern because of its toxic and non-degradable properties in natural environments (Bhaumik et al. 2011; Srivastava et al. 2015). Chromium acts as a carcinogen, mutagen and teratogen in biological systems (Bhaumik et al. 2011). Therefore, it is harmful to human health even at very low concentrations and has been categorized as a group I human carcinogen by the International Agency for Research on Cancer (Fang et al. 2014). The World Health Organization (WHO) recommended 0.05 mg/L as a maximum allowable concentration of total chromium in drinking water, whereas the US Environmental Protection Agency has set 0.1 mg/L as a maximum contaminant level for total chromium in drinking water (WHO 2004; Zhang et al. 2015). Considering these properties, it should be treated with suitable physicochemical and/or biological treatment processes. Several treatment technologies have been used to treat water and wastewater contaminated with organic compounds and heavy metals, especially chromium, such as ion exchange (Rengaraj et al. 2001), electro coagulation (Ölmez 2009), reduction (Ma et al. 2012), adsorption (Liu et al. 2010), carbon nanotube aerogels (Mikhlanov et al. 2016) and
carbon nanotube fibers, thin films and aerogels (Suksabye et al. 2007; Tran et al. 2015). However, some of these processes have several disadvantages, such as high initial installation cost, generation of chemical wastes and high energy requirement (Debnath & Ghosh 2008). Among them, adsorption technique has been widely used because it is simple, efficient and requires low operating cost (Dubey & Gopal 2007; Fang et al. 2014). Scallop, widely found in oceans and seas, is a marine bivalve mollusk of the Pectinidae family (Shirzad-Siboni et al. 2014a). Many manufacturers of marine products and a large number of restaurants discharge scallop shells as wastes (Shirzad-Siboni et al. 2014a). They can be recycled as an economical adsorbent (Shirzad-Siboni et al. 2014a). When the adsorption capacity of the used adsorbents has been exhausted, they should be separated from aqueous solution using a filtration method and regenerated (Lasheen et al. 2014). However, as filtration is a tedious process causing blockage in filters, magnetic separation has been widely applied because it produces no contaminants and can treat a large amount of wastewater within a short span of time (Lasheen et al. 2014). Magnetite (Fe₃O₄), having super-paramagnetic property, can be recovered very quickly by an external magnetic field and is easily reused without losing its active property (Yuan et al. 2010). Hence, the Scallop shell particles combined with Fe₃O₄ can be used as an alternative to the traditional adsorbents.

In this study Scallop shell was magnetized by coating the magnetite nanoparticles onto the surface of the Scallop shell. These Scallop shell-Fe₃O₄ nanoparticles were used for the adsorption of Cr(VI) from aqueous solutions. The effects of pH, adsorbent dosage, initial Cr(VI) concentration, ionic strength and temperature in different time intervals on the removal efficiency of Cr(VI) were studied. Adsorption kinetic, isotherm and thermodynamic studies were undertaken to investigate adsorption mechanism and maximum adsorption capacity of Scallop shell-Fe₃O₄ nanoparticles.

**MATERIALS AND METHODS**

**Chemicals**

Iron(III) chloride (FeCl₃.6H₂O), iron(II) chloride (FeCl₂.4H₂O), K₂Cr₂O₇, 1,5-diphenyl-carbazide, sodium hydroxide, sodium chloride, sodium sulphate, sodium bicarbonate, sodium carbonate and hydrochloric acid, which were of analytical grade, were purchased from Merck (Germany) and used without any purification. Scallop shell sample was collected from a sea beach in the city of Caspian Sea in Guilan province of Iran, and then was washed with deionized water and dried in sunlight. The details about pretreatment and main compositions for the Scallop shell are reported in our previous work (Shirzad-Siboni et al. 2014a). Stock solution (1,000 mg/L) of Cr(VI) was prepared by dissolving K₂Cr₂O₇ into distilled water and kept in a refrigerator. The initial pH of the solution was adjusted by addition of 0.1 M NaOH or HCl, and measured by pH meter (Metron, Switzerland). The experiments were carried out at room temperature (25 ± 2 °C).

**Magnetization of the Scallop shell-Fe₃O₄ nanoparticles**

Scallop shell-Fe₃O₄ nanoparticles were prepared via the co-precipitation method (Nethaji et al. 2015; Mohagheghian et al. 2015). The appropriate amounts of FeCl₃.6H₂O (0.2 M) and FeCl₂.4H₂O (0.1 M) were dissolved in 200 mL deionized water. Scallop shell was added to the suspension at 1:1 volume ratio. 25% NH₄OH (25 mL) was added drop-wise to the precursor solution to obtain an alkaline medium (pH = 8) producing a black and gelatinous precipitate of Scallop shell-Fe₃O₄ nanoparticles under nitrogen gas. It was heated at 80 °C for 2 h with continuous stirring. The desired Scallop shell-Fe₃O₄ nanoparticles were collected by a permanent magnet and then washed with deionized water and ethanol five times. Then they were dried at 80 °C in vacuum for 5 h. For characterization of the functional groups, size, surface morphology, main compositions and magnetic property of the samples, Fourier transform infrared spectroscopy (FT-IR, Mira3, Tescan, Czech Republic), X-ray diffraction (XRD, Mira3, Tescan, Czech Republic), scanning electron microscopy (SEM, Mira3, Tescan, Czech Republic), energy dispersive X-ray (EDX, Mira3, Tescan, Czech Republic) and Vibrating Sample Magnetometer (VSM, MDKFD, Iran), respectively, were used. Point of zero charge (pHₚzc) was determined to investigate surface charge properties of the adsorbents. The pHₚzc of Scallop shell-Fe₃O₄ nanoparticles was determined adopting the method previously used (Farrokhi et al. 2014; Shirzad-Siboni et al. 2014b).

**Adsorption experiments**

The adsorption experiments were carried out in a 1,000 mL Erlenmeyer flask containing 30 mL of Cr(VI) solution and 3 g of Scallop shell-Fe₃O₄ nanoparticles. The mixtures were continuously stirred (150 rpm) at room temperature for different time intervals (2–240 min). At specified time
intervals, 10 mL solution was taken from the solution and was separated from the mixture solution by permanent magnet for 1 min to remove Scallop shell-Fe$_3$O$_4$ nanoparticles from the samples. The residual concentration of Cr(VI) was measured using a colorimetric method by adding 2 mL 1,5-diphenyl-carbazide solution (0.5 g 1,5-diphenyl-carbazide dissolved in 100 mL acetone) to form a complex, by using a UV/Visible spectrophotometer (Hach DR 5000, USA) at $\lambda_{\text{max}}$ of 540 nm according to standard methods for the examination of water and wastewater (Water and Environment Federation & American Public Health Association 2003). In order to study effects of various parameters, experiments were conducted at different amounts of adsorbent (0.25 to 3 g/L), initial Cr(VI) concentrations (5 to 50 mg/L), initial pH (3 to 11) and temperature (298 to 323 K). Reusability of adsorbent is an important factor for the application of developed adsorbent in the treatment of wastewater. Hence, desorption of adsorbed Cr(VI) from the surface was performed using deionized water, 0.1 M NaOH and HNO$_3$. The adsorption of Cr(VI) was performed by the regenerated Scallop shell-Fe$_3$O$_4$ nanoparticles for eight repeated runs.

RESULTS AND DISCUSSION

Adsorbent characterization

SEM and VSM analysis

A photographic image of Scallop shell and SEM images of Scallop shell, Fe$_3$O$_4$ and Scallop shell-Fe$_3$O$_4$ nanoparticles are shown in Figure 1(a)–1(d), respectively. Figure 1(d) clearly illustrates the distribution of magnetite nanoparticles over the surface of Scallop shell. An average size of Fe$_3$O$_4$ nanoparticles was around 10 nm. VSM was used to measure...
magnetic property of Fe₃O₄ and Scallop shell-Fe₃O₄ nanoparticles. The VSM magnetization curve of the Fe₃O₄ and Scallop shell-Fe₃O₄ nanoparticles at room temperature is shown in Figure 2. The saturated magnetization value of Fe₃O₄ and Scallop shell-Fe₃O₄ nanoparticles was 58.97 emu/g and 25.78 emu/g, respectively. These results indicated that the Scallop shell-Fe₃O₄ nanoparticles showed an excellent magnetic response to a magnetic field. Therefore, they could be separated easily and rapidly due to the high magnetic sensitivity. To identify crystal structure, mean crystal size, phase purity, functional groups and elemental composition of the Fe₃O₄ and Scallop shell-Fe₃O₄ nanoparticles, XRD, FT-IR and EDX were used (data was in the previous work) (Mohagheghian et al. 2015). XRD and FT-IR analysis also showed coating of Fe₃O₄ onto Scallop shell. According to the EDX analysis, the major elements were Fe, O, Ca and Cl, indicating formation of Scallop shell-Fe₃O₄ nanoparticles.

**Effect of parameters on the removal of Cr(VI) with Scallop shell-Fe₃O₄ nanoparticles**

**Effect of solution pH**

The effect of pH on the Cr(VI) (30 mg/L) adsorption onto Scallop shell-Fe₃O₄ nanoparticles (2 g/L) was investigated between pH 3 and 11 and the results are shown in Figure 3. Solution pH is recognized as one of the important parameters that govern the adsorption process. Figure 3 shows that removal efficiency decreased by increasing the solution pH. Indeed, the removal efficiency decreased from 87.7% to 28.8% by increasing the solution pH from 3 to 11. And the adsorption capacity decreased from 13.16 to 4.32 mg/g when the solution pH increased from 3 to 11 (Figure 3). Generally, surface charge of the adsorbents and speciation of ionic contaminants is variable with variation of solution pH (Liu et al. 2011). Removal efficiency was maximum at pH 3. Indeed, the removal efficiency was enhanced from 38.7 to 87.7% by increasing the contact time from 2 to 240 min at pH 3. The favorable removal of Cr(VI) at a lower pH might be related to an anionic-type adsorption of Cr(VI) onto Scallop shell-Fe₃O₄ nanoparticles because the dominant form of Cr(VI) is $\text{HCrO}_4^-$ and the surface of the adsorbent is positively charged at low pH (pH = 3). But the portion of negative charge on the surface of adsorbent is gradually increased with increasing solution pH. The decreased adsorption of Cr(VI) with increasing solution pH can be explained by the $pH_{zpc}$ value of Scallop shell-Fe₃O₄ nanoparticles (Lin et al. 2014; Mutongo et al. 2014). According to the previous work, the $pH_{zpc}$ of Fe₃O₄ and Scallop shell-Fe₃O₄ nanoparticles is 6 and 11, respectively (Mohagheghian et al. 2015). Thus, the Scallop shell-Fe₃O₄ nanoparticles acquire a negative surface charge at the solution pH above $pH_{zpc}$. At a pH lower than $pH_{zpc}$, the surface of Scallop shell-Fe₃O₄ nanoparticles acquires positive charge, and Cr(VI) molecules also have less
negative charge (Chen et al. 2014; Mohagheghian et al. 2015). Stability of Scallop shell-Fe₃O₄ nanoparticles has been assessed at different solution pH. The results showed that Scallop shell-Fe₃O₄ nanoparticles were stable in acidic solutions (pH > 2). Since the most effective removal of Cr(VI) was observed at pH 3, the other experiments were performed at this pH. Similar observations were also reported by other research groups (Bhattacharya et al. 2006; Babu & Gupta 2008; Al-Sou'od 2012).

Effect of adsorbent dosage and contact time

The influence of adsorbent dosage on the removal of Cr(VI) was investigated in the range of 0.25–3 g/L at pH 3 with variation of reaction time (Figure 4). Indeed, the removal efficiency increased from 35.3 to 94.9% by increasing the adsorbent dosage from 0.25 to 3 g/L over the entire reaction time (2–240 min). This trend can be explained by the increased active sites with the increase of the adsorbent dosage. As shown in Figure 4, the removal rate of Cr(VI) at all dosages was rapid in the first stages of contact time (9 min) and then it gradually slowed until reactions reached a near equilibrium after 240 min. The rapid adsorption at initial reaction time may be attributed to the abundance of free active sites on the surface of Scallop shell-Fe₃O₄ nanoparticles and their easy availability for Cr(VI) molecules (Yuan et al. 2010; Nethaji et al. 2015; Ataabadi et al. 2015).

As the active sites were occupied by Cr(VI), adsorption rates were decreased due to having few available active sites on the adsorbents (Yuan et al. 2010; Nethaji et al. 2015; Ataabadi et al. 2015). Nevertheless, the adsorption capacity decreased from 42.33 to 9.48 mg/g when the adsorbent dosage increased from 0.25 to 3 g/L (Figure 4). This result can be explained by the presence of a relatively lower amount of adsorbate than adsorbent, causing increase of unsaturated adsorption sites based on unit amount of adsorbent (Yuan et al. 2010; Nethaji et al. 2015; Ataabadi et al. 2015). However, Cr(VI) removal (%) increased from 35.3 to 94.9% when the adsorbent dosage increased from 0.25 to 3 g/L (Figure 4). Indeed, the removal efficiency was enhanced from 34.8 to 94.9% by increasing the contact time from 2 to 240 min at 3 g/L adsorbent. Since the most effective removal (%) of Cr(VI) was observed at 3 g/L, the other experiments were performed at this adsorbent dosage.

Effect of initial Cr(VI) concentration

Removal efficiency of Cr(VI) was studied by varying the initial Cr(VI) concentration from 5 to 50 mg/L at constant adsorbent dosage (3 g/L) and at pH 3 (Figure 5). When the initial Cr(VI) concentration was increased from 5 to 50 mg/L, the removal efficiency of Cr(VI) was decreased from 99.99 to 72.7%. This result can be explained by the fact that the adsorbent has a limited number of active sites and thus
becomes saturated above a certain Cr(VI) concentration (Yuan et al. 2010; Nethaji et al. 2013; Ataabadi et al. 2015). All surface sites of the Scallop shell-Fe3O4 nanoparticles used in this work were occupied when Cr(VI) concentration was above 20 mg/L, showing below 100% adsorption. Nevertheless, the adsorption capacity increased from 1.66 to 18.17 mg/g when the initial Cr(VI) concentration increased from 5 to 50 mg/L (Figure 5). Similar observations were also reported for the removal of Cr(VI) (Chowdhury & Yanful 2010; Nethaji et al. 2013; Lasheen et al. 2014).

Effect of ionic strength

There are various kinds of anions in the water and wastewater, such as chloride, sulfate, carbonate and bicarbonate, which may have positive or negative effects on adsorption. To assess the effect of different types of anions such as Cl\(^{-}\), CO\(_3^{2-}\), HCO\(_3^{-}\) and SO\(_4^{2-}\) on the removal efficiency of Cr(VI), constant amounts of NaCl, Na\(_2\)CO\(_3\), NaHCO\(_3\) and Na\(_2\)SO\(_4\) (30 mg/L) were added to a batch reactor before beginning the adsorption at constant concentration of Cr(VI) (30 mg/L) and adsorbent dosage (5 g/L) at pH 3 (Figure 6). Removal efficiency of Cr(VI) was quite similar in the presence of sodium bicarbonate (95.3%) and sodium chloride (94.0%) compared with a control test (94.9%). However, slightly decreased removal efficiency was observed in the presence of sodium carbonate (84.7%). Figure 6 shows that removal efficiency of Cr(VI) decreased in the presence of CO\(_3^{2-}\) and SO\(_4^{2-}\). This removal trend can be explained by the fact that these two anions may occupy active sites on the adsorbent, which can reduce adsorption efficiency. Any anions such as Cr(VI), which can be adsorbed onto the surface of adsorbent through outer-sphere association, are strongly sensitive to type of background electrolytes. Thus, the decreased Cr(VI) adsorption in the presence of CO\(_3^{2-}\) and SO\(_4^{2-}\) may be due to the competition on the surface of the adsorbent.

Comparison of each process and desorption efficiency

Removal efficiency of Cr(VI) by Scallop shell, Fe\(_3\)O\(_4\) and Scallop shell-Fe\(_3\)O\(_4\) nanoparticles was compared at an initial Cr(VI) concentration (50 mg/L), an adsorbent dosage (5 g/L) and at pH 3. Figure 7 shows that removal efficiency for each process was 26.4, 71.9 and 94.9%. These experiments demonstrate that both Scallop shell and Fe\(_3\)O\(_4\) nanoparticles are needed for the effective removal of Cr(VI).

For determination of the impacts of desorption efficiency, eight experiments were performed in the following conditions: initial Cr(VI) concentration (30 mg/L), an adsorbent dosage (5 g/L) and at pH 3 (Figure 8). The removal efficiency at each run was Run 1 (94.9%) washing with deionized water, Run 2 (86.0%), Run 3 (82.6%), Run 4 (77.6%), Run 5 (0.1 M NaOH, 96.7%), Run 6 (0.1 M NaOH, 93.2%),

![Figure 6](https://iwaponline.com/wst/article-pdf/75/10/2369/452549/wst075102369.pdf)

**Figure 6** | The effect of ionic strength on the removal of Cr(VI) by Scallop shell coated with Fe\(_3\)O\(_4\) nanoparticles at different time intervals (pH – 3, initial Cr(VI) concentration – 30 mg/L, adsorbent dose – 3 g/L, 298 K).

![Figure 7](https://iwaponline.com/wst/article-pdf/75/10/2369/452549/wst075102369.pdf)

**Figure 7** | The contribution of each process involved in the removal of Cr(VI) by Scallop shell coated with Fe\(_3\)O\(_4\) nanoparticles at different time intervals (pH – 3, initial Cr(VI) concentration – 30 mg/L, adsorbent dose – 3 g/L, 298 K).
Run 7 (0.1 M NaOH, 88.8%) and Run 8 (HNO₃, 82.1%). As shown in Figure 8, adsorption capacity of Cr(VI) by Scallop shell-Fe₃O₄ nanoparticles was maintained up to eight consecutive runs, suggesting a plausible adsorbent in the treatment of Cr(VI) from water and wastewater.

Kinetic, equilibrium and thermodynamic studies

Adsorption kinetic experiments were performed at different Cr(VI) concentrations (5 to 50 mg/L), at constant adsorbent dosage (3 g/L) and at pH 3. The pseudo-first-order, pseudo-second-order and intra-particle-diffusion models were applied in order to find an efficient model for the description of adsorption. The relevant equations for the kinetic, equilibrium and thermodynamic studies are shown in Table 1 (Azizian 2004; Liu & Liu 2008; Shirzad et al. 2011; Babaei et al. 2015; Mahmoudi et al. 2018). To obtain kinetic data for the removal of Cr(VI), ln (1 – q_t/q_e) versus t, t/q_t versus t and q_t versus t^0.5 was plotted for the pseudo-first-order, pseudo-second-order and intra-particle-diffusion model, respectively. The kinetic parameters for the removal of Cr(VI) at different initial Cr(VI) concentrations and pHs by pseudo-first-order, pseudo-second-order and intra-particle-diffusion models are summarized in Tables 2 and 3, respectively. The kinetic data for Cr(VI) adsorption showed the best fitting (R^2 = 0.9987) with the pseudo-second-order model. Moreover, when the initial Cr(VI) concentration increased from 5 to 50 mg/L, the values of k_2 (g/mg-min) and R^2 for the pseudo-second-order model were decreased from 2.355 to 0.0046 g/mg-min and from 1 to 0.9877, respectively. Also, q_e (mg/g) was increased from 1.66 to 12.57 mg/g. This result indicated that adsorption data were in agreement with this model. The value of C was measured as 3.324 mg/g, indicating that intra-particle diffusion is not the only controlling step for Cr(VI) adsorption and the process is controlled by boundary layer diffusion to some degree. To investigate the adsorption equilibrium isotherm, experiments were performed with 30 mg/L Cr(VI) as an initial concentration using various adsorbent dosages (0.4–15 g/L) at pH 3 for 72 h. All experiments were repeated three times and average values were reported. Langmuir and Freundlich equations

![Figure 8](image-url)
were applied to fit experimental adsorption data, and the related equations are shown in Table 1 (Azizian 2004; Liu & Liu 2008; Shirzad et al. 2011; Mahmoudi et al. 2013). $R_L$ value (separation factor) expresses a characteristic of the Langmuir isotherm. Generally adsorption will be favorable when the $R_L$ value is between 0 and 1 (Azizian 2004; Liu & Liu 2008; Shirzad et al. 2011), while unfavorable adsorption will be expected when the $R_L$ value is above 1. $R_L$ values 1 and 0 mean linear and irreversible adsorptions, respectively.

To obtain equilibrium data, $c_e/q_e$ versus $c_e$ and log $q_e$ versus log $c_e$ were plotted for the Langmuir and Freundlich models, respectively. The Freundlich and Langmuir isotherm constants at different temperature are given in Table 4. The value of correlation coefficient $R^2 = 0.9982$, $R^2 = 0.9798$ and $R^2 = 0.978$ at temperature of 298 K, 303 K and 323 K indicates that adsorption of Cr(VI) onto the Scallop shell-Fe$_3$O$_4$ nanoparticles follows the Freundlich isotherm. The monolayer saturation capacity at temperature of 298 K, 303 K and 323 K was 34.48, 31.85 and 28.01 mg/g, respectively. Thermodnamic experiments were performed at different temperatures from 298 to 323 K at constant adsorbent dosage (3 g/L) and at pH 3 (Figure 9). When the temperature was increased from 298 to 323 K, Cr(VI) removal efficiency was decreased from 94.9 to 78.0%. The related equations are shown in Table 1 (Liu & Liu 2008). From a linear plot between ln $K_L$ and $1/T$, $\Delta H$ (kJ mol$^{-1}$) and $\Delta S$ (J mol$^{-1}$ K$^{-1}$) were calculated from the slope and intercept, respectively. The values of $\Delta S$, $\Delta H$, $\Delta G$ and $q_m$ at different temperatures are given in Table 4. $\Delta H$ (kJ mol$^{-1}$) was a negative value. This means adsorption is favorable at low temperature. The removal capacity of Cr(VI) by Scallop shell-Fe$_3$O$_4$ nanoparticles was compared with that by other adsorbents in Table 4. Maximum adsorption capacity at temperature of 298 K was obtained as 34.48 mg/g and 6.66 mg/g at pH 3 and 7, respectively. Based on the obtained results, the Scallop shell-Fe$_3$O$_4$ nanoparticles can be regarded as an efficient adsorbent for removal of Cr(VI) from water and wastewater.

### CONCLUSIONS

Super paramagnetic Scallop shell-Fe$_3$O$_4$ nanoparticles with 25.78 emu/g were used for the removal of Cr(VI) from...
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<td>2.25</td>
<td>0.9679</td>
<td>55</td>
</tr>
<tr>
<td>298</td>
<td>Magnetic</td>
<td>2.94</td>
<td>3.62</td>
<td>0.991</td>
<td>3.55</td>
</tr>
<tr>
<td>308</td>
<td>Magnetic</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>318</td>
<td>Magnetic</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

*(continued)*
aqueous solutions. The prepared sample was characterized by SEM and VSM. Adsorption of Cr(VI) was dependent on the initial Cr(VI) concentration and pH of the solution. The removal efficiency was maximum at pH 3 and was increased with increasing contact time and adsorption dosage, but was decreased with increasing initial Cr(VI) concentration and temperature. Adsorption kinetics of Cr(VI) onto adsorbent was better described by a pseudo-second-order model than by pseudo-first-order and intra-particle-diffusion models. Cr(VI) adsorption onto Scallop shell-Fe₃O₄ nanoparticles was better described by a Freundlich model than a Langmuir model. The maximum adsorption capacity of Cr(VI) by Scallop shell-Fe₃O₄ nanoparticles was 34.48 to 28.01 mg/g at temperatures ranging from 298 to 323 K. Scallop shell-Fe₃O₄ nanoparticles were identified as an effective and environmentally friendly adsorbent for the removal of Cr(VI) from wastewater due to an efficient removal ability and separation property.

**ACKNOWLEDGEMENTS**

The authors thank the Guilan and Iran Universities of Medical Sciences of Iran for their contributions.
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