Removal of chromium(III) ions from aqueous solutions using different types of hydroxyapatites

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ABSTRACT

This study explored the possibility of using hydroxyapatite and its two modifications as sorbents to remove Cr(III) ions under different experimental conditions. The effect of pH (3–7), chromium concentration (10–100 mg L–1) and time (5–60 min) on adsorption was investigated. The Langmuir, Freundlich and Temkin adsorption models were applied to describe experimental data. Maximum adsorption capacity constituted 78.1 mg g–1 for hydroxyapatite treated with pluronic P123, 79.7 mg g–1 for hydroxyapatite and 134 mg g–1 for hydroxyapatite treated with pluronic F127 surfactant. The pseudo-first-order, pseudo-second-order, Elovich and intraparticle diffusion models were used to describe the kinetics of the process. For all sorbents, the experimental data fitted very well the pseudo-second-order and intraparticle diffusion models. The obtained results showed the potential of synthesized sorbents to be used for Cr(III) removal from wastewater.

Keywords: Chromium(III); Adsorption; Hydroxyapatite; Flame atomic adsorption spectrometry

1. Introduction

Water contamination caused by heavy metals deserves increasing attention in many counties today, mainly due to their high toxicity, non-biodegradable nature and high accumulation capacity [1]. Conventional techniques of heavy metal removal from industrial effluents include precipitation, flocculation, filtration, evaporation, solvent extraction, sorption, ion-exchange, electrodialysis, and membrane separation processes [2,3]. Often these techniques are expensive or ineffective at metal concentrations in solution less than 100 mg L–1 [4]. Thus, there is a great need to develop cheap and eco-friendly techniques for environmental remediation. Adsorption has been considered as one of the most efficient methods because of the possibility to archive high removal efficiency and its low operation cost [1]. The hydroxyapatite is an ideal sorbent for long-term containment of contaminants because of its high adsorption capacity, low water solubility, high stability under reducing and oxidizing conditions, good thermal stability, availability, and low cost [5,6]. Hydroxyapatite has a high removal capacity, mainly for divalent heavy metal ions and has been used for wastewater treatment [5–8].

Among the toxic heavy metal species present in the environment, chromium pollution of the water resources is a major problem because of the high toxicity of its compounds.
Cr(VI) is considered as the most toxic chromium species, however, Cr(III) is even considered as an important microelement for biochemical processes that can be converted in Cr(VI) under oxidative conditions, thus representing a potential risk for the environment and human health. In addition, chromium is prevalently introduced in the environment from anthropogenic sources in form of Cr(III) ions. Chromium(III) is released in water bodies from all the industrial activities involving the manufacturing or the application of metal alloys, metalliferous mining, electroplating, batteries, paints and pigments production, landfill leachate, electronics, manures sewage sludge, paper and pulp industry, and petroleum refinement [6,9,10].

The objective of this study was to test hydroxyapatite and two modifications of it as alternative adsorbent materials for the removal of Cr(III) ions from aqueous solutions. The effect of contact time, initial concentration, and pH on Cr(III) adsorption was investigated. Equilibrium and kinetic studies were performed in order to describe the adsorption process.

2. Materials and methods

Calcium nitrate, chromium nitrate and phosphoric acid as well as surfactants (pluronic P123 and pluronic F127) were purchased from Sigma-Aldrich (Germany). Ethylic alcohol and liquid ammonia were purchased from Chemical Company. All chemicals were reagent grade and were used without further purification.

2.1. Sorbents synthesis

Hydroxypatite (HAP) was prepared by co-precipitation of calcium nitrate and phosphoric acid according to the synthesis reported by Arsad et al. [11] with some modifications. An aqueous solution of 0.5 M calcium nitrate was added to 50 mL ethanol and was vigorously stirred at room temperature. The pH of the solution was adjusted to 10 by addition of 25% (v/v) ammonia in the solution. The 0.3 M phosphoric acid was added slowly in a dropwise manner to allow reacting with calcium nitrate. After 1 h reaction at 60°C, the reaction mixture was kept to age overnight at room temperature to complete the reaction. Then, the suspension was centrifuged at 4,000 rpm for 15 min, separated and dried at room temperature. The white powder of the sample was calcined for 6 h at 550°C and labeled as HAP.

\[ 10\text{Ca(NO}_3)_2 + 6\text{H}_3\text{PO}_4 + 2\text{H}_2\text{O} \rightarrow \text{Ca}_{10} (\text{PO}_4)_6 \text{O} + 20\text{HNO}_3 \]  

(1)

The HAP P123 and HAP F127 sorbents were obtained following the same procedure except that the corresponding surfactants were added to the reaction mixture. Thus, the pluronic P123 was used to synthesize HAP P123 sample, and pluronic F127 to synthesize HAP F127.

2.2. Adsorption experiments

The adsorption experiments were performed placing 0.02 g of sorbent in a 50 mL flask with 10 mL of a solution containing chromium at constant agitation. To determine the adsorption capacity of sorbents the effect of pH (3.0–7.0), time (5–60 min), Cr(III) concentration (10–100 mg L⁻¹) on chromium adsorption from batch solutions was studied. After experiments, the sorbent was separated from the solution by filtration and chromium concentration in the solution was determined. Experiments were performed in triplicate and the average of measurements was used in the calculation.

The chromium uptake \( q \) was calculated using the following equation:

\[ q = \frac{V(C_i - C_f)}{m} \]  

(2)

and adsorption removal efficiency, \( R \) (%) from the equation:

\[ R = \frac{C_i - C_f}{C_i} \times 100 \]  

(3)

where \( q \) is the amount of metal ions adsorbed on the sorbent, mg g⁻¹; \( V \) is the volume of solution, L; \( C_i \) is the initial concentration of metal in mg L⁻¹, \( C_f \) is the final metal concentration in the solution, mg L⁻¹, and \( m \) is the mass of sorbent, g.

2.3. Methods

The \( N_2 \) adsorption/desorption isotherms for Brunauer–Emmett–Teller specific surface area measurements were recorded on a NOVA 2200e (Quantachrome Instruments, USA) automated gas adsorption analyzer. Before analysis, the samples were outgassed at 120°C for at least 6 h under vacuum. Chromium concentration in solution was determined at a resonance line of 357.9 nm by applying flame atomic absorption spectrometer (Kvant-2, Russia). The calibration solutions were prepared from a 1 g L⁻¹ chromium stock solution (Atomic Absorption Spectroscopy standard solution; Merck, Germany). Infrared spectra were recorded in the range of 4,000–400 cm⁻¹ using a Bruker Alpha Platinum-ATR spectrometer (Bruker Optics, Ettingen, Germany).

3. Results and discussion

3.1. Sorbents characterization

Nitrogen adsorption–desorption analysis was performed in order to characterize the porous structure of the synthesized sorbents. Fig. 1 shows typical isotherms characteristic to HAPs. According to the International Union of Pure and Applied Chemistry classification, the obtained isotherm obey type IV, containing hysteresis loops, which indicates the presence of mesopores in the adsorbent structure.

The textural characteristics of the investigated sorbents are presented in Table 1. The obtained data show that the addition of the surfactant P123 leads to a significant increase of specific surface area and total pore volume of the HAP in comparison with untreated HAP. With the addition of F127, the pore volume remains almost on the level of untreated HAP, while the specific surface area was reduced.

Fig. 2 represents the control of Fourier-transform infrared spectroscopy (FTIR) of HAP and its two modifications.
The FTIR spectra of the sorbents show characteristic bands due to presence of PO$_4^{3-}$ ions ($\nu_1 = 963$ cm$^{-1}$, $\nu_2 = 870$ cm$^{-1}$, $\nu_3 = 1,036$ and 1,095 cm$^{-1}$, $\nu_4 = 568$ and 600 cm$^{-1}$) [12]. In the structure of HAP are bounded hydroxyl functional groups but the presence of stretching vibration of HO– groups were not revealed by FTIR analysis. It could be caused by the ionic bond of HO– groups or as a result of interference bonds due to the symmetry of molecules. In FTIR spectra of HAP P123 and HAP F127 was observed a slight increase in the intensity of deformation bands of PO$_4^{3-}$ ions.

In the infrared spectra of Cr-loaded sorbents was observed the shifting of bands positions of PO$_4^{3-}$ ions and change of frequencies (Fig. 3), which indicates their involvement in chromium ions binding.

The reduction of the intensity of PO$_4^{3-}$ bands can be associated with the Cr(III) ions exchange with the protons and Ca(II) ions present on the HAP surface and coordination of Cr(III) with PO$_4^{3-}$ [3,9]. This finding was supported by Deydier et al. [13], who found that Cr(III) ions binding to hydroxyapatite involves three successive steps: surface complexation of Cr(III) ions, HAP dissolution followed by Cr$_{6n}$(PO$_4$)$_6$(OH)$_2$ precipitation and slow metal diffusion/substitution of Ca(II) ions.

### 3.2. Effect of pH dependence of adsorption process

The effect of initial solution pH on Cr(III) removal was studied in the pH range 3.0–7.0. Experiments were not performed at pH < 3.0 since the removal of cations can be limited by electrostatic repulsion between the positively charged surface of the sorbent and cations [14]. According to data presented in Fig. 4 the highest Cr(III) removal was achieved at pH 5.0 for HAP and HAP P123: 97% and 97.6%, respectively. Maximum Cr(III) removal by HAP F127 was reached at pH 6.0 (98%). Even at pH 3.0 Cr(III), removal was not lower than 60%. According to Leyva-Ramos et al. [15] Cr(III) in dependence of the pH exists in the solutions in different forms: the predominant species below pH 2 is Cr$^{3+}$ and between pH 6.5 and 10 the predominant species is Cr(OH)$_2$. At pH 3 Cr$^{3+}$ (90%) and CrOH$^+$ (10%) at pH 3. At pH 4, Cr(III) is present in solution in the form of Cr$^{3+}$ (40%) and Cr(OH)$^{2+}$ (60%), at pH 5 in the form of Cr(OH)$^{3+}$ (70%) and Cr$_2$(OH)$_4$ (20%) and at pH 6 Cr(OH)$^{2+}$ (40%), Cr(OH)$_2$ (35%) and Cr$_3$(OH)$_4$ (25%).
Wakamura et al. [16] in their study proposed two mechanisms of Cr(III) ions adsorption on the HAP (i) cation-exchange with Ca(II) ion or (ii) anion exchange with H$_2$PO$_4^{-}$ ions. It should be mentioned that anion exchange was possible at pH > 8 when chromium is present in solution in the Cr(OH)$_4^{-}$ form. Maximum removal efficiency at pH 5–6, where chromium(III) is present in solution in the form of Cr$^{3+}$, CrOH$_2^{+}$ and Cr$_3$(OH)$_5^{5+}$ suggests that cation-exchange is the main mechanism of Cr(III) ions adsorption by HAP and its two modifications. Ferri et al. [6] showed that the mechanism of Cr-trapping on HAP surface at pH 4–6 is surface complexation or ionic exchange.

Fig. 2. FTIR spectra of (a) HAP, (b) HAP P123 and (c) HAP F127 control samples.[TS: Label (a), (b), (c) from bottom to top]

Fig. 3. FTIR spectra of Cr-loaded sorbents (a) HAP, (b) HAP P123 and (c) HAP F127
3.3. Effect of contact time on the adsorption process

Contact time between adsorbent and adsorbed is related to the period needed for the establishment of the equilibrium within the adsorption system. The effect of contact time on the adsorption of Cr(III) ions on the three sorbents was studied in a range of 0–60 min. For all studied sorbents the equilibrium was achieved in 45 min when 89% of Cr(III) was removed by HAP, 97% by HAP-P123 and 96% by HAP-F127 (Fig. 5).

Contact time between adsorbent and adsorbate helps the understanding of adsorption kinetics since it provides important information with regard to mechanisms that control the adsorption process. The adsorption kinetic data were analyzed using the four most common kinetic models, namely, pseudo-first-order, pseudo-second-order, Elovich and intraparticle diffusion models. The models are expressed by the following formulas:

**Pseudo-first-order model**:

\[
\log(q_e - q_t) = \log q_e - \frac{k_1 t}{2.303}
\]

where \(q_e\) and \(q_t\) are the amounts of chromium(III) (mg g\(^{-1}\)) adsorbed at equilibrium and at \(t\) (min) time, respectively, and \(k_1\) (min\(^{-1}\)) is the rate constant of pseudo-first-order.

**Pseudo-second-order model**:

\[
t = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}
\]

where \(k_2\) (g mg\(^{-1}\) min\(^{-1}\)) is the rate constant of second-order.

**Elovich model**:

\[
q_t = \frac{1}{\beta} \ln(\alpha \beta) + \frac{1}{\beta} \ln(t)
\]

where \(\alpha\) and \(\beta\) are the Elovich equation constants.

**Weber and Morris intraparticle diffusion model**:

\[
q = k_{\text{diff}} t^{1/2} + C_i
\]

where \(k_{\text{diff}}\) is the intraparticle diffusion rate constant (mg g\(^{-1}\) min\(^{-1/2}\)), \(C_i\) is the intercept, giving an idea about the thickness of the boundary layer.

The experimental kinetic data were described according to the indicated models (Fig. 6) and the coefficients of determination, as well as the kinetic parameters of Cr(III) adsorption on studied sorbents, are given in Table 2.

The coefficients of determination \(R^2\) show that the experimental results for Cr(III) ions on all analyzed sorbents are well described by the pseudo-second-order kinetic model. The pseudo-second-order model is based on the assumption that the rate-limiting step of the adsorption may be chemical adsorption or chemisorption involving valency forces through sharing or exchange of electrons between sorbent and sorbate [17]. The pseudo-second-order adsorption kinetics well fitted the adsorption of Cr(III), ions on HAP nanoparticles [3]. For Elovich and the pseudo-first-order model, the coefficient of determination values was significantly lower.

The intraparticle diffusion often plays an important role in the adsorption process when adsorbent is porous materials since it allows us to predict the rate-controlling step. In case when the plot of \(q_t\) vs. \(t^{1/2}\) is linear and the line pass through the origin then intraparticle diffusion is considered the rate-controlling step. If the plot does not pass through the origin is an indication that the intraparticle diffusion is not the only rate-limiting step, but also other kinetic models may control the rate of adsorption, all of which may be operating simultaneously [18]. From Fig. 7 it is seen that there are three stages of Cr(III) adsorption (i) the first linear sharp region might due to the instantaneous adsorption of Cr(III) ions on the external surface of adsorbent; (ii) the second phase is the gradual adsorption phase, where the intraparticle diffusion is a rate-limiting step and (iii) the third
The positive value of \( K_R \) for any of the phases (Fig. 7) it can be suggested that the uptake [21]. At Cr(III) concentration in solution, the pollutant between the aqueous and solid phases, thus driving force to overcome all mass transfer resistances of it is shown in Fig. 8 adsorption capacity of sorbents increases with the increase of Cr(III) concentration in solution.

region is attributed to the final equilibrium stage where the adsorption process starts to slow down due to the high affinity of adsorbate adsorbed on the adsorbent surface [19].

Since the plot of \( q \) vs. \( t^{1/2} \) did not pass through the origin for any of the phases (Fig. 7) it can be suggested that the intraparticle diffusion is not the only rate-controlling step. The positive value of \( C_{s} \) obtained for all sorbents depicts boundary layer effects [20].

### 3.4. Effect of the initial concentration of Cr(III) ions on the adsorption process

The adsorption of Cr(III) ions was carried out at Cr(III) concentration in the solution ranging from 10 to 100 mg L\(^{-1}\). As it is shown in Fig. 8 adsorption capacity of sorbents increases with the increase of Cr(III) concentration in solution.

A higher initial concentration provides an important driving force to overcome all mass transfer resistances of the pollutant between the aqueous and solid phases, thus increases the uptake [21]. At Cr(III) concentration in solution, 100 mg L\(^{-1}\) the adsorption capacity of studied sorbents was almost the same: 27 mg g\(^{-1}\) for HAP, 30.5 mg g\(^{-1}\) for HAP P123 and 28 mg g\(^{-1}\) for HAP F127, respectively.

The isotherms data were analyzed using three commonly used equilibrium models: Langmuir, Freundlich and Temkin. The mathematical expressions of the linear form of applied models are given by Eqs. (8)–(11), respectively:

\[
\frac{1}{q_e} = \frac{1}{q_{\text{max}}} + \frac{1}{b q_{\text{max}} C_e}
\]  

where \( C_e \) is metal ions concentration at equilibrium (mg L\(^{-1}\)), \( q_e \) is the amount of metal adsorbed at equilibrium (mg g\(^{-1}\)), \( q_{\text{max}} \) is maximum adsorption capacity of the sorbent (mg g\(^{-1}\)) and \( b \) is Langmuir adsorption constant (L mg\(^{-1}\)). \( K_F \) is a constant that is important in calculating the dimensional parameter \( (R_L) \) that explains the favorability of the adsorption process; \( R_L \) is calculated using the equation given below:

\[
R_L = \frac{1}{1 + K_F C_o}
\]  

where \( R_L > 1 \) the adsorption process is unfavorable; \( R_L = 1 \) adsorption is linear; \( 0 < R_L < 1 \) adsorption process is favorable; \( R_L = 0 \) adsorption is irreversible.

\[
\ln q_e = \ln K_F + \frac{1}{n} \ln C_e
\]

where \( q_e \) is the amount of metal adsorbed at equilibrium (mg g\(^{-1}\)), \( C_e \) is concentration of metal ions in aqueous solution at equilibrium (mg L\(^{-1}\)); \( K_F \) and \( n \) are Freundlich constants that include factors that affect adsorption capacity and adsorption intensity, respectively.

\[
q_e = \frac{RT}{b_T} \ln K_T + \frac{RT}{b_T} \ln C_e
\]

where \( T \) is the absolute temperature (K), \( R \) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)), \( K_T \) is the equilibrium binding constant (L mg\(^{-1}\)), and \( b_T \) is the variation of adsorption energy (kJ mol\(^{-1}\)). \( T \) is Temkin constant related to the heat of adsorption (kJ mol\(^{-1}\)). In the above equation, \( B = RT/b_T \).

The adsorption isotherms for Cr(III) ions adsorption on HAP and its two modifications are presented in Fig. 9.

The coefficients of determination (\( R^2 \)) and isotherm parameters from the linear regressive method are listed in Table 3.

According to the calculated values of the coefficients of determination, the Freundlich isotherm model represented the poorest fit of experimental data (\( R^2 \) 0.93 for all sorbents). The isotherm is considered valid for weak van der Waals type adsorption as well as for strong chemisorption [22]. The \( 1/n \) value calculated from the Freundlich isotherm model was less than unity for all systems, indicating that the adsorption of Cr(III) onto HAP and its two modifications was favorable.

The Langmuir model was found to fit well experimental data for all three analyzed sorbents. The Langmuir isotherm is based on the assumption that uptake occurs on a homogenous surface by monolayer adsorption without interaction between adsorbed molecules [23]. It is suggested that HPO\(_4\) groups play the main role in Cr(III) ions binding. The maximal theoretical adsorption capacity of analyzed sorbent increased in the following order HAP < HAP P123 < HAP F127. The \( R_L \) values between 0 and 1 indicate favorable adsorption. It should be mentioned that the maximum adsorption capacity of HAP treated with pluronic F127 surfactant was approximately two times higher than for the other two sorbents. In Si et al. [3] study it was shown that the Langmuir adsorption isotherm well fitted the adsorption data for the

### Table 2

Kinetic parameters of the adsorption of chromium(III) ions

<table>
<thead>
<tr>
<th>Kinetic model</th>
<th>Sorbent</th>
<th>HAP</th>
<th>HAP F127</th>
<th>HAP P123</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo-first-order</td>
<td></td>
<td>4.3</td>
<td>4.6</td>
<td>4.6</td>
</tr>
<tr>
<td>( q_{\text{exp}} ) (mg g(^{-1}))</td>
<td></td>
<td>1.6</td>
<td>2.6</td>
<td>2.7</td>
</tr>
<tr>
<td>( k_1 ) (min(^{-1}))</td>
<td>0.03</td>
<td>0.1</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.98</td>
<td>0.94</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>Pseudo-second-order</td>
<td></td>
<td>4.3</td>
<td>4.6</td>
<td>4.6</td>
</tr>
<tr>
<td>( q_{\text{exp}} ) (mg g(^{-1}))</td>
<td></td>
<td>4.4</td>
<td>4.8</td>
<td>4.85</td>
</tr>
<tr>
<td>( k_1 ) (g mg(^{-1}) min(^{-1}))</td>
<td>0.28</td>
<td>0.25</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.998</td>
<td>0.999</td>
<td>0.999</td>
<td></td>
</tr>
<tr>
<td>Elovich model</td>
<td></td>
<td>44.4</td>
<td>24.6</td>
<td>14.1</td>
</tr>
<tr>
<td>( \alpha ) (g mg(^{-1}) min(^{-1}))</td>
<td>2.1</td>
<td>1.67</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>( \beta ) (g mg(^{-1}))</td>
<td>2.3</td>
<td>2.1</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.89</td>
<td>0.88</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Intraparticle diffusion (for linear stage)</td>
<td></td>
<td>0.37</td>
<td>0.35</td>
<td>0.33</td>
</tr>
<tr>
<td>( k_{\text{diff}} ) (mg g(^{-1}) min(^{1/2}))</td>
<td>2.3</td>
<td>2.1</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.96</td>
<td>0.94</td>
<td>0.95</td>
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</tbody>
</table>

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The isotherms data were analyzed using three commonly used equilibrium models: Langmuir, Freundlich and Temkin. The mathematical expressions of the linear form of applied models are given by Eqs. (8)–(11), respectively:
Fig. 6. Kinetics of chromium(III) adsorption on hydroxyapatites: (a) pseudo-first-order, (b) pseudo-second-order and (c) Elovich model.

Fig. 7. A plot of intraparticle diffusion modeling of Cr(III) adsorption onto hydroxyapatites.

Fig. 8. Adsorption of chromium ions as the function of chromium concentration in solution (temperature 20°C; sorbent dosage 0.02 g; contact time 1 h).
adsorption of Cr(III) ions on HAP nanoparticles as compared to the Freundlich adsorption isotherm. Coefficients calculated for the Temkin model for HAP and HAP F127 were on the level of those obtained for Langmuir models, while for HAP P123 coefficient of determination calculated from the Temkin model was lower (0.91). The Temkin isotherm takes into account the interactions between adsorbents and metal ions to be adsorbed and is based on the assumption that the free energy of adsorption is a function of the surface coverage and adsorption is characterized by a uniform distribution of the binding energies, up to some maximum binding energy [24]. The Temkin constant (B) values related to the heat of adsorption were in the range of 9.4–10.7 kJ mol⁻¹. It has been reported by Ho et al. [25] that the typical range of bonding energy for the ion-exchange mechanism is 8–16 kJ mol⁻¹. The positive value of bT indicates the endothermic character of Cr(III) ions adsorption.

Comparison of adsorption capacity of the analyzed sorbents and the data obtained for other sorbents are presented in Table 4.

4. Conclusions

Cr(III) adsorption on HAP and its two modifications was studied as a function of pH, Cr(III) concentration and

<table>
<thead>
<tr>
<th>Table 3: Adsorption isotherm parameters</th>
</tr>
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<tr>
<td><strong>Model</strong></td>
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<tr>
<td>----------</td>
</tr>
<tr>
<td>q_exp</td>
</tr>
<tr>
<td>Langmuir</td>
</tr>
<tr>
<td>q_max (mg g⁻¹)</td>
</tr>
<tr>
<td>b (L g⁻¹)</td>
</tr>
<tr>
<td>R²</td>
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<tr>
<td>Freundlich</td>
</tr>
<tr>
<td>Kf</td>
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<tr>
<td>1/n</td>
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<td>R²</td>
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</tr>
<tr>
<td>bT</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>R²</td>
</tr>
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</table>

Fig. 9. Isotherm plots of HAP, HAP P123 and HAP F127 adsorbents for Cr(III) removal (a) Langmuir, (b) Freundlich and (c) Temkin.
time of interaction. According to calculated parameters, the adsorption of Cr(III) ions on studied sorbents followed the second-order kinetic model, and the intraparticle diffusion mechanism was the dominating control process. The Langmuir, Freundlich and Temkin adsorption models were evaluated in order to assess the efficiency of the preparation mechanism of Cr(III) ions onto sorbents. It was found that the maximum Cr(III) adsorption capacity of analyzed sorbents is 78.1 mg g⁻¹ HAP, 79.7 mg g⁻¹ for HAP and 134 mg g⁻¹ for HAP P123, 79.7 mg g⁻¹ for maximum Cr(III) adsorption capacity of analyzed sorbents. It was found that the used for the mathematical description of the adsorption equilibrium of Cr(III) ions onto sorbents. The kinetic model investigation on chromium(III) sorption by animal bones, Chemosphere, 52 (2005) 315–320.

Table 4

<table>
<thead>
<tr>
<th>Sorbent</th>
<th>pH</th>
<th>( q_m ) mg g⁻¹</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>HAP</td>
<td>5</td>
<td>27</td>
<td>Present study</td>
</tr>
<tr>
<td>HAP P123</td>
<td>5</td>
<td>30.5</td>
<td>Present study</td>
</tr>
<tr>
<td>HAP F127</td>
<td>5</td>
<td>28</td>
<td>Present study</td>
</tr>
<tr>
<td>Bone char</td>
<td>5</td>
<td>78.6</td>
<td>[9]</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>5</td>
<td>23</td>
<td>[15]</td>
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<tr>
<td>Animal bones</td>
<td>5</td>
<td>39–194</td>
<td>[8]</td>
</tr>
<tr>
<td>Amberlite IR-120 resin</td>
<td>–</td>
<td>67.7</td>
<td>[26]</td>
</tr>
<tr>
<td><em>Jatropha curcas</em> L.</td>
<td>5.5</td>
<td>16</td>
<td>[10]</td>
</tr>
<tr>
<td>Vesicular basalt rock</td>
<td>6</td>
<td>0.9</td>
<td>[27]</td>
</tr>
</tbody>
</table>

Acknowledgment

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References