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Adsorption characteristics of bovine serum albumin onto $\alpha$-Fe$_2$O$_3$ nanoparticles prepared via the alcohol solution combustion process of ferric nitrate

Yongjin Li$^{1,5}$, Ziye Zhu$^{2,5}$, Zhixiang Lv$^{3,5}$$^\ast$, Zhou Wang$^4$ and Yuefang Chen$^1$$^\ast$

1 School of Medicine, Jiangsu University, Zhenjiang 212013, People’s Republic of China
2 School of Pharmacy, Jiangsu University, Zhenjiang 212013, People’s Republic of China
3 The People’s Hospital of Danyang, Affiliated Danyang Hospital of Nantong University, Zhenjiang 212300, People’s Republic of China
4 College of Vanadium and Titanium, Panzhihua University, Panzhihua 617000, People’s Republic of China
5 These authors contributed equally to this work as first authors.

E-mail: chen_yuefang@163.com

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Abstract

The $\alpha$-Fe$_2$O$_3$ nanoparticles were prepared via the alcohol solution combustion process of ferric nitrate. The scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), and vibrating sample magnetometer (VSM) were taken to characterize the prepared $\alpha$-Fe$_2$O$_3$ nanoparticles. The average particle sizes of the as-prepared $\alpha$-Fe$_2$O$_3$ nanoparticles were approximately 180 nm, and their magnetic property was approximately 0.42 emu·g$^{-1}$ after the measurement. The different concentrations of BSA solutions and the adsorption times were investigated to investigate the adsorption characteristics of bovine serum albumin (BSA) onto $\alpha$-Fe$_2$O$_3$ nanoparticles. For larger adsorption capacity and higher removal rate, the dose of $\alpha$-Fe$_2$O$_3$ nanoparticles in aqueous solution was selected at 2.5 mg·ml$^{-1}$. The adsorption process of BSA onto $\alpha$-Fe$_2$O$_3$ nanoparticles conformed to the pseudo-first-order kinetic model. While, the correlation coefficient (R$^2$) of the Temkin isothermal model was higher than Langmuir model and Freundlich isothermal model, suggesting that the isothermal model of BSA onto $\alpha$-Fe$_2$O$_3$ nanoparticles was more in line with Temkin isotherm model. Which suggested that the adsorption behavior of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles for BSA belonged to multi-molecular layer chemisorption. When BSA concentration was 600 mg·l$^{-1}$ and the pH of solution was 5, the adsorption capacity of BSA onto magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles achieved 114.2 mg·g$^{-1}$, and the adsorption rate could still reach 70.3% of the first time after 7 cycles.

1. Introduction

Magnetic nanomaterials are a novel kind of developed material in recent years, they are widely applied in many areas owing to their unique properties [1]. Among them, the applications of magnetic nanomaterials in biological medicine area attract more and more attention [2–7]. The species of magnetic nanomaterials are numerous, of which, iron oxide-based magnetic nanomaterials are most [8, 9]. However, in consideration of the biosecurity, ferric oxide nanoparticles become the preferred magnetic nanomaterials [10].

Of ferric oxide nanoparticles, magnetic Fe$_2$O$_3$ nanoparticles have become a research hotspot because of their characteristics [11]. First and foremost, the size of magnetic Fe$_2$O$_3$ nanoparticles is easy to control [12]. Secondly, magnetic Fe$_2$O$_3$ nanoparticles have the advantages of magnetism and simple operation [13]. On one hand, they can be fully dispersed in the absence of an external magnetic field. On the other hand, they can be rapidly enriched and separated under the condition of an external magnetic field. Third, magnetic Fe$_2$O$_3$ nanoparticles are easy to be modified, because magnetic Fe$_2$O$_3$ nanoparticles contain rich hydroxyl groups on the surface and are easily compounded with other nanomaterials [14]. In addition, good recyclability is a great property of Fe$_2$O$_3$ nanoparticles. Magnetic Fe$_2$O$_3$ nanoparticles can be reused after proper cleaning [15-18].
Therefore, magnetic Fe₂O₃ nanoparticles are a kind of multi-functional material due to their good magnetic orientation, biocompatibility, and biodegradability [19]. In biological medicine area, magnetic Fe₂O₃ nanoparticles show potential application prospects in the field of biological separation [20, 21], biosensor detection [22, 23], nuclear magnetic resonance (NMR) imaging [24], targeted drugs [25, 26], immunoassay [27], and enzyme immobilization [28]. Among which, their utilizations in protein purification [29] and nucleic acid detection [30] reveal the promising prospect and significance.

Magnetic α-Fe₂O₃ nanoparticles could be prepared via many approaches, such as, hydrothermal method [31], pyrolytic process [32], coprecipitation method [33], sol-gel method [34, 35], surfactant assisted reflux method [36]. These methods have some disadvantages of long preparation period, complicated operation and high cost. Compared with these methods, the combustion-calcination method has many advantages of simple operation, low equipment requirement and particle size easy to control.

In this project, we prepared magnetic α-Fe₂O₃ nanoparticles via the ethanol solution of iron nitrate combustion-calcination process, which would provide research basis for the construction of drug delivery system in living organisms; and with bovine serum albumin (BSA) [37] as the model of biological macromolecule due to its representativeness, low price and easy purification [38, 39], the adsorption capacity and mechanism of BSA onto α-Fe₂O₃ nanoparticles were revealed.

2. Experimental details

2.1. Preparation and characterization of α-Fe₂O₃ nanoparticles

Magnetic α-Fe₂O₃ nanoparticles were prepared via the ethanol solution of iron nitrate combustion-calcination process. First of all, 10.27 g of iron nitrate was dissolved in 20 ml of anhydrous ethanol, stirred evenly under the magnetic stirring apparatus. Then, the homogeneous solution was placed in the crucible and ignited. The combustion product was naturally cooled to room temperature, and then transferred into a programmed temperature control furnace, calcined at 700 °C for 2 h, and finally ground to obtain α-Fe₂O₃ nanoparticles. The morphology of α-Fe₂O₃ nanoparticles was characterized by scanning electron microscopy (SEM), the elementary composition was measured by the energy dispersive spectroscopy (EDS), X-ray diffraction (XRD) was used to perform the phase identification of the nanomaterials while the vibrating sample magnetometer (VSM) was utilized to measure their magnetic property, and FTIR was carried out at 4000–400 cm⁻¹ with potassium bromide as the carrier.

2.2. Adsorption determination

In order to study the effect of magnetic α-Fe₂O₃ nanoparticles dose on adsorption capacity, at room temperature and pH of 7, various doses of magnetic α-Fe₂O₃ nanoparticles (4 mg, 5 mg, 6 mg, 7 mg, 8 mg) were put in 2 ml 600 mg l⁻¹ of BSA solution and kept for 3 h, respectively. Then the mixtures were centrifuged for 10 min, and the absorbencies of the supernates were measured by ultraviolet spectrophotometer, and the adsorption quantity of BSA per unit weight of α-Fe₂O₃ nanoparticles at time t was figured by the following equation [40]:

\[ q_t = \frac{V(C_0 - C_t)}{m} \]

Where V represents the volume of the solution (L), and m is the mass of adsorbent (g), C₀ and Cₜ respectively represent the initial concentration and the concentration of BSA at time t (mg l⁻¹).

2.2.1. Adsorption kinetics research

5 mg of α-Fe₂O₃ nanoparticles prepared with 20 ml of absolute ethyl alcohol and calcined at 700 °C for 2 h were put in 2 ml of BSA solution in various concentrations (400 mg l⁻¹, 600 mg l⁻¹, 800 mg l⁻¹, and 1000 mg l⁻¹) and kept for different times (5 min, 10 min, 15 min, 20 min, 25 min, 30 min, 35 min, 40 min, 60 min, 80 min, 100 min, 120 min, and 140 min). After that, the mixtures were centrifuged for 10 min, and the UV absorption intensities of the supernatants at 280 nm were measured. The adsorption capacities were calculated. The abscissa was set as the adsorption time and the ordinate was set as the adsorption capacity. The optimal adsorption kinetics model was determined according to the correlation coefficients of pseudo-first-order, pseudo-second-order, and intraparticle diffusion models.

2.2.2. Adsorption isotherms research

5 mg of α-Fe₂O₃ nanoparticles were put in 2 ml of BSA solutions in various concentrations at room temperature. The mixtures were then ultrasound for 5 min and kept for 3 h. After adsorption equilibrium, the mixtures were centrifuged for 10 min, and the absorbances of the supernatant were measured at 280 nm. The adsorption
capacities were calculated. The abscissa was set as the equilibrium solution concentration while the ordinate was set as the adsorption capacity. The optimal adsorption isotherm model was determined based on the correlation coefficients of Langmuir, Freundlich, and Temkin isothermals models.

2.3. Effect of pH on adsorption capacity and cycle performance of $\alpha$-Fe$_2$O$_3$ nanoparticles

In order to study the influences of pH and cycle number of $\alpha$-Fe$_2$O$_3$ nanoparticles on adsorption capacity, 1 M HCl and NaOH solutions were used to adjust the pH (4, 5, 6, 7, 8, 9, 10) of BSA solutions at room temperature. 5 mg of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles was put in 2 ml 600 mg l$^{-1}$ BSA solution and kept for 3 h, then the mixtures were centrifuged for 10 min, and the UV absorption intensities of the supernatants at 280 nm were measured, and the adsorption capacities under various pH values were compared. While, 50 mg of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles was put in 20 ml 600 mg l$^{-1}$ BSA solution and kept for 3 h, then centrifuged, and the adsorption capacity of $\alpha$-Fe$_2$O$_3$ nanoparticles for BSA was examined. Then the $\alpha$-Fe$_2$O$_3$ nanoparticles adsorbed BSA were recalcined at 700 °C for 2 h, and repeated the above BSA adsorption process, the cycle performance of $\alpha$-Fe$_2$O$_3$ nanoparticles for adsorption of BSA was revealed.

3. Results and discussion

3.1. Characteristics of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles

The characteristics of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles were depicted in figure 1. The SEM morphology in figure 1(A) showed that prepared $\alpha$-Fe$_2$O$_3$ nanoparticles were spherical and had a certain amount of aggregation with an average particle size of approximately 180 nm. The elemental composition of $\alpha$-Fe$_2$O$_3$ nanoparticles in figure 1(B) revealed that the nanoparticles were composed of Fe and O and the atomic percentage of Fe to O was approximately 2:3, which verified the successful preparation of $\alpha$-Fe$_2$O$_3$ nanoparticles. Figure 1(C) exhibited the XRD pattern of prepared $\alpha$-Fe$_2$O$_3$ nanoparticles compared with that of hematite standard PDF card (JCPDS No. 33-0664). It could be seen from the figure that the positions and sizes of characteristic peaks of the prepared nanoparticles were consistent with those of the standard hematite cards. The diffraction peaks located at 24.1°, 33.2°, 35.6°, 40.9°, 49.5°, 54.1°, 62.4°, and 63.9° belong to (012), (104), (110), (113), (024), (116), (214) and (300) diffraction crystals, which proved the composition of the prepared nanoparticles was $\alpha$-Fe$_2$O$_3$ [41, 42].
magnetic property of prepared \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles measured in figure 1(D) was approximately 0.42 emu·g\(^{-1}\).

3.2. Effect of magnetic \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles dosage

The dosage of magnetic \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles had great influence on the adsorption. As shown in figure 2, with the dose of magnetic \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles increasing from 2 mg L\(^{-1}\) to 4 mg L\(^{-1}\), the adsorption capacity decreased gradually, and the removal rate of BSA increased gradually. When the dosage of magnetic \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles increased from 2 mg L\(^{-1}\) to 2.5 mg L\(^{-1}\), the BSA removal rate was significantly improved. The reason was that with the increase of magnetic \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles dose, the adsorption sites increased \([43, 44]\). But the removal rate had no significant change when the dosage of adsorbent increased from 2.5 mg L\(^{-1}\) to 4 mg L\(^{-1}\). The reason was that the adsorption sites overlap with the increase of magnetic \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles dose, limiting the adsorption capacity of the surface \([45]\). Hence, the optimal dosage of magnetic \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles for BSA adsorption was 2.5 mg L\(^{-1}\).
3.3. Adsorption of BSA onto magnetic α-Fe₂O₃ nanoparticles

3.3.1. Adsorption kinetics

Pseudo-first-order model, pseudo-second-order model, and intraparticle diffusion model were utilized to fit the experimental data [46], and the adsorption capacity of BSA in aqueous solution onto α-Fe₂O₃ nanoparticles at room temperature was further investigated.

The equations of pseudo-first-order model, pseudo-second-order model, and intraparticle diffusion model were as follows.

\[ q_t = q_e(1 - e^{-k_1t}) \]  

where \( q_e \) and \( q_t \) are the amounts of BSA adsorbed at equilibrium and at any time \( t \), respectively; \( k_1 \) (min⁻¹) is the adsorption rate constant for corresponding model; \( x_i \) was the constants of intraparticle diffusion model.

Table 1. Fitted kinetics parameters for adsorptions of BSA in aqueous solution onto α-Fe₂O₃ nanoparticles at room temperature.

| Kinetic models               | Equations                                      | Parameters | Initial concentration of BSA (mg·ml⁻¹) |
|-----------------------------|------------------------------------------------|------------|---------------------------------------|
| Pseudo-first-order model    | \( q_t = q_e(1 - e^{-k_1t}) \)                | \( q_e \)  | 44.7804  67.0575  82.3967  94.4879   |
|                             |                                                | \( k_1 \)  | 0.0421  0.0398  0.0369  0.0424       |
| Pseudo-second-order model   | \( q_t = \frac{q_e^2k_2t}{1 + q_ek_2t} \)      | \( k_2 \)  | 0.0009  0.0005  0.0004  0.0004       |
| Intraparticle diffusion model| \( q_t = x_i + k_i t^{1/2} \)                 | \( k_i \)  | 3.5521  5.4741  6.8366  7.3912       |

Figure 4. Fit of the pseudo-first-order kinetics model, pseudo-second-order kinetics model and intraparticle diffusion kinetics model at initial concentrations of BSA equal to 0.4 mg·ml⁻¹ (A), 0.6 mg·ml⁻¹ (B), 0.8 mg·ml⁻¹ (C), and 1.0 mg·ml⁻¹ (D).
Where, \( q_e \) (mg·g\(^{-1}\)) and \( q_t \) (mg·g\(^{-1}\)) were the amounts of BSA adsorbed at equilibrium and at any time \( (t) \), respectively; \( k_1 \) (min\(^{-1}\)), \( k_2 \) (g·mg\(^{-1}\)·min\(^{-1}\)) and \( k_i \) (mg·g\(^{-1}\)·min\(^{-1}\)) were the adsorption rate constants for corresponding model; \( x_i \) was the constant of intraparticle diffusion model.

Relevant fitted kinetics parameters for adsorptions of BSA in aqueous solution onto \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles were listed in table 1. Figure 3 showed the adsorption kinetics curves of magnetic \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles when the initial concentration of BSA solution were 0.4 mg·ml\(^{-1}\), 0.6 mg·ml\(^{-1}\), 0.8 mg·ml\(^{-1}\), and 1.0 mg·ml\(^{-1}\). As the concentration of BSA solution increased, so did the adsorption capacity. This phenomenon suggested that the binding of \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles to BSA was weak, but the binding of BSA to BSA was strong owing to the formation of layers of protein on the surface of \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles. The adsorption rate increased quickly and then slowly until equilibrium was reached when the concentration was constant. The reason was that the biggest saturated adsorption capacity of the material was greater than the content of BSA in the solution at the beginning of the adsorption process. More binding sites had not been completely adsorbed by BSA molecules. Therefore, the adsorption rate was fast in that there are a lot of BSA molecules that could bind to nanomaterials. As the material adsorption binding sites were gradually bound, the adsorption sites were reduced and the adsorption rate was slow. When all sites were bound, the adsorption reached saturation and the rate did not change \[47\]. Figure 4 showed the fitting curves of three different adsorption kinetics models. The correlation coefficients were low when the pseudo-second-order kinetic model and intraparticle diffusion model were utilized to fit the experimental data, while the correlation coefficients were above 0.98 when the pseudo-first-order kinetic model was employed, suggesting that the adsorption of BSA onto \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles conformed to the pseudo-first-order kinetic model, which indicated that the electrostatic force acted as the dominant effects of total amount of BSA adsorbed.

### 3.3.2. Adsorption isotherms

Figure 5 exhibited the fitting curves of three different adsorption isothermal models: Langmuir model, Freundlich isothermal model, and Temkin isothermal model \[48\].

The assumption of Langmuir model was that monolayer adsorption occurred on homogeneous surfaces \[47\]. The formula of Langmuir model was formula (5).

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

Where, \( q_e \) (mg·g\(^{-1}\)) was the adsorption capacity at BSA adsorption equilibrium, \( q_{\text{max}} \) (mg·g\(^{-1}\)) was the maximum adsorption capacity of BSA onto \( \alpha \)-Fe\(_2\)O\(_3\) nanoparticles, \( C_e \) (mg·l\(^{-1}\)) was adsorption equilibrium concentration of BSA, \( K_L \) was the equilibrium constant of Langmuir model.
The assumption of Freundlich isothermal model was that multimolecular layer adsorption occurred on heterogeneous surfaces \[45\]. The formula of Freundlich isothermal model was formula \((6)\).

\[
q_e = K_F C_e^1/n
\]

Where, \(q_e\) (mg g\(^{-1}\)) was the adsorption capacity at BSA adsorption equilibrium, \(C_e\) (mg l\(^{-1}\)) was adsorption equilibrium concentration of BSA, \(K_F\) was the equilibrium constant of Freundlich isothermal model. The parameter \(1/n\) of Freundlich isothermal model was 0.6382 which was between 0 and 1, indicating that the adsorption of BSA onto magnetic \(\alpha\)-Fe\(_2\)O\(_3\) nanoparticles was favorable \[45, 49\].

The assumption of Temkin isothermal model was that mixed adsorption of monolayer and multilayer adsorption \[48\]. The formula of Temkin isothermal model was formula \((7)\).

\[
q_e = B \ln(A_T C_e)
\]

\(q_{max}\) was the maximum adsorption capacity of BSA onto \(\alpha\)-Fe\(_2\)O\(_3\) nanoparticles; \(K_L, K_F, K_R, 1/n, A_T,\) and \(B\) were constants for corresponding model.

The assumption of Freundlich isothermal model was that multimolecular layer adsorption occurred on heterogeneous surfaces \[45\]. The formula of Freundlich isothermal model was formula \((6)\).

\[
q_e = K_F C_e^1/n
\]

Where, \(q_e\) (mg g\(^{-1}\)) was the adsorption capacity at BSA adsorption equilibrium, \(C_e\) (mg l\(^{-1}\)) was adsorption equilibrium concentration of BSA, \(K_F\) was the equilibrium constant of Freundlich isothermal model. The parameter \(1/n\) of Freundlich isothermal model was 0.6382 which was between 0 and 1, indicating that the adsorption of BSA onto magnetic \(\alpha\)-Fe\(_2\)O\(_3\) nanoparticles was favorable \[45, 49\].

The assumption of Temkin isothermal model was that mixed adsorption of monolayer and multilayer adsorption \[48\]. The formula of Temkin isothermal model was formula \((7)\).
Where, $q_e$ (mg·g$^{-1}$) was the adsorption capacity at BSA adsorption equilibrium, $B$ and $A_T$ were constants of Temkin isothermal model, $C_e$ (mg·l$^{-1}$) was adsorption equilibrium concentration of BSA.

Table 2 showed the fitting calculation parameters of the three isothermal models. By comparing the correlation coefficients ($R^2$), it could be seen that the correlation coefficients ($R^2$) of the Temkin isothermal model were higher than those of the other two models, indicating that this isothermal model was more suitable for describing the adsorption mechanism of this experiment, the adsorption was mainly affected by electrostatic action. The Langmuir isothermal adsorption model could be excluded in figure 5, indicating a multilayer BSA adsorption on magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles.

The maximum adsorption capacities of BSA onto magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles and the other adsorbents were listed in table 3, it was obvious that the adsorption of BSA onto magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles was greater than those of the other adsorbents, which suggested the promising prospect of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles in biomedical field.

3.4. FTIR of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles

The infrared spectrum of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles, BSA, post-adsorption magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles and re-calcined magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles were shown in figure 6. Compared figure 6(b) with figure 6(c), the peak at 1654 cm$^{-1}$ was the characteristic peak of carbonyl stretching vibration of the amide I bond and 1540 cm$^{-1}$ was the characteristic peak of N–H bending and C–N stretching of the amide II bond, the peak at 2923 cm$^{-1}$ was the characteristic peak of CH$_2$, the peaks at 551 cm$^{-1}$ and 472 cm$^{-1}$ were the characteristic peak of the Fe–O bond, indicating that the adsorption of BSA onto magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles$^{[37, 53–56]}$. Compared figure 6(c) with figure 6(d), it was obvious that BSA had been removed from magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles after re-calcination. This indicated that BSA was adsorbed onto magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles rather than reacting with magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles.

3.5. Effect of pH on adsorption capacity

The initial pH of BSA had a great influence on the adsorption capacity of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles. As shown in figure 7, the adsorption capacity of BSA onto magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles reached the maximum value of 114.2 mg·g$^{-1}$ when the pH value of BSA solution was 5. The adsorption capacity increased when the value of pH increased from 4 to 5. The reason was that the surface of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles and BSA had a positive charge, BSA would produce electrostatic repulsion with magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles and the positive charge of BSA was decreasing. The adsorption capacity decreased gradually when the pH value of BSA solutions increased from 5 to 10. The reason was that the increase of hydroxyl in the solution would preempt the adsorption site of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles with BSA, which led to the decrease of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles’ adsorption capacity$^{[40, 50]}$. 

$$q_e = B \ln \left( A_T C_e \right)$$  (7)
3.6. Cycle performance of $\alpha$-Fe$_2$O$_3$ nanoparticles

Cycle number was an important index to evaluate the performance of adsorbents. As shown in figure 8, with the increase of the cycle number, the adsorption rate of BSA onto $\alpha$-Fe$_2$O$_3$ nanoparticles decreased gradually, and the adsorption rate could still reach 70.3% of the first time after 7 cycles. The reason was that the adsorbent active sites of magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles were occupied, in the process of re-calcination, partial pore collapse resulted in the reduction of adsorption sites [40]. The results indicated that magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles had good cyclic regeneration and had good application value.

4. Conclusions

(1) Magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles were prepared via the ethanol solution of iron nitrate combustion-calcination process, they were spherical with an average particle size of approximately 180 nm and the saturation magnetization of approximately 0.42 e mu g$^{-1}$.

(2) The adsorption of BSA onto $\alpha$-Fe$_2$O$_3$ nanoparticles conformed to the pseudo-first-order kinetic model, the isothermal model of BSA onto $\alpha$-Fe$_2$O$_3$ nanoparticles was more consistent with Temkin isotherm model. Therefore, the adsorption behavior of BSA onto magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles belonged to multi-molecular layer adsorption.

(3) The adsorption capacity of BSA onto magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles reached the maximum when pH was 5 and the adsorption rate could still reach 70.3% of the first time after 7 cycles, indicating that magnetic $\alpha$-Fe$_2$O$_3$ nanoparticles had good cyclic regeneration and application prospect.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Zhixiang Lv @ https://orcid.org/0000-0002-3461-8592
Yuefang Chen @ https://orcid.org/0000-0002-2169-4211

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