Preparation of Chitosan Poly(methacrylate) Composites for Adsorption of Bromocresol Green

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ABSTRACT: In the present study, chitosan poly(methacrylate) composites were prepared and applied for adsorption of bromocresol green from aqueous solutions. The synthesized composites were characterized with scanning electron microscopy, Fourier transform infrared spectroscopy, and thermogravimetric analysis. The bromocresol green removal by the developed adsorbent was investigated, and the effects of experimental parameters, including sample pH and adsorption time, were also examined. Furthermore, the adsorption characteristics of the synthesized adsorbent, including kinetics, adsorption isotherms, and thermodynamics, were comprehensively studied. The adsorption isotherm was well described by the Freundlich model, and the maximum adsorption capacity was 39.84 μg mg⁻¹ by shaking for 40 min at pH 2.0. Bromocresol green adsorption kinetics followed a pseudo-second-order kinetic model, indicating that adsorption was the rate-limiting step. Thermodynamic parameters and the negative values of Gibbs free energy change (ΔG°) showed that adsorption was a spontaneous process. The positive values of entropy change (ΔS°) implied that the adsorption of bromocresol green on chitosan poly(methacrylate) composites was an increasing random process. In addition, enthalpy change (ΔH°) values were positive, suggesting that the adsorption of bromocresol green was endothermic. The adsorption percentage of bromocresol green with chitosan poly(methacrylate) composites remained above 97% after three times of recycling test.

1. INTRODUCTION

Bromocresol green (BCG) (2,6-dibromo-4-[7-(3,5-dibromo-4-hydroxy-2-methyl-phenyl)-9,9-dioxo-8-oxa-9,16-thiabicyclo[4.3.0]nona-1,3,5-trien-7-yl]-3-methyl-phenol) belongs to the triphenylmethane family dyes that is used as a pH indicator and as a tracking dye for DNA agarose gel electrophoresis. It is more stable, and its biodegradation is more difficult because of complex aromatic molecular structures. Furthermore, it has an impact on the aquatic life and food web even in low concentrations. Many of the industrial dyes disturb both the environment and living beings and have even proved as cancer-causing substances. Therefore, removing them from aqueous solutions is of great interest. It is for this reason that analytical methods have been developed, such as liquid–liquid extraction, membrane separation, solid-phase microextraction, and adsorption, and so forth. Adsorption methods based on application of efficient adsorbent are extensively employed. A variety of materials such as activated carbon, zeolite, imprinted materials, inorganic materials, sorption resins, and polymers have been reported for adsorption of dyes in this technique. Nonetheless, researchers are attracted toward finding new materials to develop novel adsorbents.

Of the above-mentioned materials, polymers have been widely used in many fields because of their abundant recognition sites, high loading capacity, and easy modification. In particular, they are used as adsorbents for adsorption of various organic substances due to their advantages of low cost, good regeneration ability, and easy recyclability. However, the defects of swelling and shrinkage lead to weak mechanical stability when polymers are exposed to different organic solvents. Recently, new polymer materials have been designed by modification with inorganic materials that have specific chemical properties, high surface-to-volume ratio, strong mechanical stability, high regenerability, and so on.

Chitosan, a linear polysaccharide composed of randomly distributed β-(1→4)-linked d-glucosamine (deacetylated unit) and N-acetyl-d-glucosamine (acylated unit), is made from chitin. It is an ideal polymer and possesses special characteristics such as nontoxicity, hydrophilicity, biocompatibility, biodegradability, adsorption properties, and so on. Chitosan carries a large number of −OH and −NH₂ groups, which is suitable for the formation of hydrogen bonds. When it is combined with polymer as cross-linking agent, the prepared composites can be used in the environment and in other fields. For instance, Kang et al. prepared hydrogels adsorbent with exfoliated montmorillonite nanosheets and chitosan for removing Methylene Blue from water. Wang et al. successfully prepared magnetic composites Fe₃O₄@SiO₂@CS-TETA-GO and applied it for the fast adsorption of Methylene Blue and Cu(II).

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In this work, chitosan poly(methacrylate) composite was prepared and characterized with scanning electron microscopy (SEM), Fourier transform infrared (FTIR) spectroscopy, and thermogravimetric analysis (TGA) to identify the structures and morphology. The obtained adsorbent was used for adsorption of bromocresol green from aqueous solutions with ultraviolet−visible spectrometry. pH value and adsorption time were investigated in the experiment. The adsorption experimental data were studied based on isotherm and kinetic models (Langmuir/Freundlich and pseudo-first-order/pseudo-second-order models). Thermodynamic parameters, the Gibbs free energy change (ΔG°), enthalpy change (ΔH°), and entropy change (ΔS°) were obtained. The results were analyzed to get sufficient knowledge of the mechanism, isotherm, kinetics, and thermodynamics of the adsorption process.

2. MATERIALS AND METHODS

2.1. Chemicals and Instruments. BCG, chitosan, glycidyl methacrylate (GMA), ethylene dimethacrylate (EDMA), α-methacrylic acid (MAA), cyclohexanol, dodecanol, and azobisisobutyronitrile (AIBN) were purchased from Macklin Reagent (Shanghai, China). Methanol, sodium dihydrogen phosphate (NaH2PO4), sodium hydrogen phosphate (Na2HPO4), sodium hydroxide (NaOH), hydrochloric acid, acetic acid, and acetone were obtained from Jiangsu Qiangsheng Chemical Co., Ltd. (Changshu, China). The properties of BCG are shown in Table 1. All other reagents were obtained from various commercial sources and were of analytical or HPLC grade.

A Cary100 ultraviolet−visible (UV−vis) spectrophotometer (Agilent Technologies Inc.) was used for the spectrophotometric analysis. Scanning electron microscopy (SEM) images were recorded on an S-3400N analyzer (JEOL Company, Japan). Fourier transform infrared (FTIR) spectra were performed using an IR200 FT-IR spectrometer (Thermo Corporation). Thermogravimetric analysis (TGA) was carried out on a Q500 apparatus (TA) from 30 to 800 °C with a heating rate of 10 °C min−1 under air atmosphere. A B11-2 magnetic stirrer (Shanghai Sile Instrument Co. Ltd, China) was applied to mix the reaction solutions. An H1650-W centrifuge (Hunan Xiangyi, China) was used for centrifuging. A pHS-3E digital pH meter (Shanghai INESA Electron Co. Ltd., China) was used for pH measurements of sample solutions.

2.2. Preparation of Chitosan Poly(methacrylate) Composites. The prepolymerization solution containing monomer (1.13 mmol GMA + 0.46 mmol MAA), cross-linker (0.62 mmol EDMA), porogen (8.99 mmol cyclohexanol + 0.54 mmol dodecanol), and initiator (0.024 mmol AIBN) was degassed by ultrasonication for about 30 min. The obtained homogeneous solution was initiated at 55 °C for 24 h to synthesize poly(MAA-GMA-EDMA) composite. Then, chitosan (1% w/v in 1% acetic acid) was added to the above-prepared composite, and this mixture was reacted at 65 °C for 4 h. After the reaction is complete, chitosan poly(methacrylate) composites (poly(GMA-MAA-EDMA)-CHT) were obtained and washed with methanol. The product was dried in an oven at 50 °C and kept in a desiccator for further use. The preparation process of poly(GMA-MAA-EDMA)-CHT is illustrated in Figure 1.

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2.3. Adsorption Experiments. The stock solutions of BCG were prepared in double-distilled water, and the UV−vis absorption wavelength of BCG was 614 nm.

To study the adsorption of poly(GMA-MAA-EDMA)-CHT toward BCG, a series of 5.0 mL of standard solutions were prepared and adjusted to pH values (1.0–10.0) with appropriate buffer solutions. Then, 10.0 mg of the poly-(GMA-MAA-EDMA)-CHT was added to the standard solution and the mixture was shaken vigorously for 40 min to facilitate adsorption of the BCG onto the poly(GMA-MAA-EDMA)-CHT. The adsorption percentage of BCG was calculated according to eq 1

\[ \text{adsorption} (%) = \frac{C_0 - C_e}{C_0} \times 100\% \]  \hspace{1cm} (1)

where \( C_0 \) and \( C_e \) are the initial and equilibrium concentrations of BCG (µg mL\(^{-1}\)), respectively.

For the equilibrium study and construction of the adsorption isotherm of BCG by poly(GMA-MAA-EDMA)-CHT, a series
of concentrations of 5.0, 10.0, 15.0, 20.0, 25.0, 30.0, 40.0, 50.0, 60.0, 70.0, 80.0, and 100.0 μg mL⁻¹ BCG standard solutions were prepared as above, adjusted to the optimum pH 2.0, and individually mixed with 10.0 mg of poly(GMA-MAA-EDMA)-CHT. The mixtures were mechanically shaken for 40 min at room temperature, and the adsorption capacity at equilibrium for BCG by poly(GMA-MAA-EDMA)-CHT was calculated using eq 2

\[ Q_e = \frac{(C_0 - C_e) \times V}{m} \]  

where \( m \) corresponds to the mass of adsorbent in (mg), \( V \) is the volume of solution in (mL), and \( Q_e \) is the adsorption capacity at equilibrium (μgm g⁻¹).

For the kinetic study, based on the effect of adsorption time on the BCG adsorption by poly(GMA-MAA-EDMA)-CHT, it was studied at different periods of time: 2, 5, 10, 20, 30, 40, 50, 60, 80, 100, and 120 min, under the same batch conditions using 5.0 μgm L⁻¹ BCG at a pH value of 2.0, and individually mixed with 10.0 mg of poly(GMA-MAA-EDMA)-CHT.

### 3. RESULTS AND DISCUSSION

#### 3.1. Characteristics of Poly(GMA-MAA-EDMA)-CHT

Figure 2 shows the SEM image of the fractured surface of poly(GMA-MAA-EDMA)-CHT. As can be seen in the figure, poly(GMA-MAA-EDMA)-CHT has a homogeneous and multiple-pore integral structure, which provided sufficient void volume and sufficient active sites. Addition of chitosan as a modifier to change the chemical or physical characteristics of polymer due to its –NH₂ and –OH groups can avoid the shrinkage and cracking of poly(GMA-MAA-EDMA)-CHT in the preparation process.

FTIR spectra of chitosan and poly(GMA-MAA-EDMA)-CHT are illustrated in Figure 3. In the spectrum of chitosan, the peak at 1028 cm⁻¹ was due to the C−O stretching of glucosamine ring and the peak at 1545 cm⁻¹ was ascribed to the N−H bending of amino group. The broad signal ranging from 3200 to 3450 cm⁻¹ comes from the O−H stretching or N−H in primary amines, and it weakens in poly(GMA-MAA-EDMA)-CHT, which could be attributed to the interaction between epoxy group of GMA and primary amines of chitosan. Poly(GMA-MAA-EDMA)-CHT showed bands at 1730 and 1640 cm⁻¹ corresponding to C=O and C=C bonds. The chitosan present in the structure of poly(GMA-MAA-EDMA)-CHT could be ascribed to O−H and/or N−H bonds (3400 cm⁻¹) and C−H bonds (2880 cm⁻¹) in the related FTIR spectrum. Accordingly, it was concluded that chitosan successfully bonded to the poly(methacrylate) composite.

Figure 4. TGA curve of poly(GMA-MAA-EDMA)-CHT.

3.2. Effects of Sample pH. Sample pH has important influence on the nature and surface properties of the adsorbent and ionization/dissociation of the adsorbate molecule. The effect of sample pH on the adsorption of BCG was investigated in the range of 1.0–10.0. Figure 5 shows that the adsorption percentage of BCG decreased when pH was increased from 1.0 to 2.0 and decreased when pH was decreased from 2.0 to 10.0. At pH = 1.0, due to excess of protons, the charges of BCG (anionic dye) and poly(GMA-MAA-EDMA)-CHT were positive, and the electrostatic attraction was less compared to that at pH = 2.0. At pH = 2.0, the electrostatic attraction favored the adsorption of BCG onto the poly(GMA-MAA-EDMA)-CHT surface due to the decrease of positive charge of BCG. Lower adsorption was expected at pH > 2.0 due to the electrostatic repulsion between BCG and anionic surface of poly(GMA-MAA-EDMA)-CHT.
percentage of BCG increased considerably until the adsorption time reached 40 min; 90.9% adsorption was achieved after 2 min, and observably increased to 98.5% after 40 min, until the maximum adsorption of 99.0% was reached after 120 min. It could also be noted that the equilibration was not linear, which means the adsorption percentage of BCG increased considerably until the adsorption time is one of the essential key factors for studying the kinetics of the adsorption process. Therefore, pH = 2.0 was selected as an optimum parameter.

### 3.3. Effect of Adsorption Time

The effect of adsorption time is one of the essential key factors for studying the kinetics of the adsorption process. The percentage adsorption of BCG by poly(GMA-MAA-EDMA)-CHT was investigated at different adsorption times ranging from 2 to 120 min. Studies were conducted using a mechanical shaker (10.0 mg of poly(GMA-MAA-EDMA)-CHT, 5.0 mL of 5.0 μg mL\(^{-1}\) BCG, at a pH of 2.0), and the results were calculated and are presented in Figure 6. It is clear from the figure that the adsorption is expressed as the adsorbate removal rate that controls the residence time of the adsorbate in the solid–solution interface.\(^{37}\) To investigate the adsorption kinetics of BCG with the adsorbents, the adsorption data were analyzed using two kinetic models (pseudo-first-order and pseudo-second-order). The linear forms are shown in eqs 3 and 4\(^4,15\)

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

Where, \(q_e\) and \(q_t\) are the amounts of BCG adsorbed at time \(t\) and at equilibrium (μg mg\(^{-1}\)), respectively; \(k_1\) is the rate constant of the pseudo-first-order models (min\(^{-1}\)); and \(k_2\) is the rate constant of the pseudo-second-order models (mg μg\(^{-1}\) min\(^{-1}\)).

The kinetic parameters obtained from eqs 3 and 4 are shown in Table 2. The comparison made between the experimental adsorption capacity (\(q_{\text{exp}}\)) values and the calculated adsorption capacity (\(q_{\text{cal}}\)) values showed that \(q_{\text{exp}}\) values were very close to \(q_{\text{cal}}\) values for the pseudo-second-order kinetic model. However, the \(q_{\text{cal}}\) values obtained from the pseudo-first-order kinetic model were different from the \(q_{\text{exp}}\) values. Moreover, the plot of pseudo-first-order kinetic model did not converge well and did not give a straight line (\(R^2 = 0.719\)). Figure 7 shows that the experimental data fit the pseudo-second-order kinetic model, which suggests that the description of the adsorption of BCG by poly(GMA-MAA-EDMA)-CHT from aqueous solution can be well described by the pseudo-second-order kinetic model.\(^{19}\)

### 3.5. Adsorption Isotherms

Isotherm studies are also undertaken to simulate the BCG adsorption by poly(GMA-MAA-EDMA)-CHT. The two most frequently used isotherms are the Langmuir and Freundlich isotherms.\(^{14,38}\) The Langmuir isotherm assumes that monolayer adsorption saturates, and no further adsorption can occur.\(^{19}\) The expression for the Langmuir isotherm is:

\[
\frac{1}{q_e} = \frac{1}{K_L q_M} + \frac{1}{q_M} \frac{1}{C}
\]

\[q_M = \frac{1}{C_e} \left( \frac{1}{1 + \frac{C}{K_L}} \right)
\]

\[
R^2 = \frac{\sum_{i=1}^{n} (q_{\text{exp}} - q_{\text{cal}})^2}{\sum_{i=1}^{n} (q_{\text{exp}} - \bar{q}_{\text{exp}})^2}
\]

**Table 2. Kinetic Parameters for the Adsorption of BCG onto poly(GMA-MAA-EDMA)-CHT**

|                | pseudo-first-order model | pseudo-second-order model |
|----------------|--------------------------|---------------------------|
| \(q_{\text{exp}}\) (μg mg\(^{-1}\)) | \(k_1\) (min\(^{-1}\))  | \(q_{\text{cal}}\) (μg mg\(^{-1}\))  | \(R^2\) | \(k_2\) (mg μg\(^{-1}\) min\(^{-1}\))  | \(q_{\text{cal}}\) (μg mg\(^{-1}\))  | \(R^2\) |
| 2.5            | 0.017                    | 0.112                     | 0.719  | 1.30                     | 2.48                          | 0.999  |

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**Figure 5.** Effect of sample pH on the adsorption of BCG onto poly(GMA-MAA-EDMA)-CHT (dosage of adsorbent: 10 mg, concentration of BCG: 5 μg mL\(^{-1}\)).

**Figure 6.** Effect of adsorption time on the adsorption of BCG onto poly(GMA-MAA-EDMA)-CHT (dosage of adsorbent: 10 mg, concentration of BCG: 5 μg mL\(^{-1}\), pH 2.0).

**Figure 7.** Pseudo-second-order kinetic model plots for the adsorption of BCG onto poly(GMA-MAA-EDMA)-CHT (dosage of adsorbent: 10 mg, concentration of BCG: 5 μg mL\(^{-1}\), pH 2.0).
where \( q_\text{e} \) and \( C_\text{e} \) are the adsorption capacity (\( \mu g \ mg^{-1} \)) and the equilibrium concentration of the adsorbate (\( \mu g \ mL^{-1} \)), respectively; \( q_{\text{max}} \) is the maximum adsorption capacity of adsorbents (\( \mu g \ mg^{-1} \)); and \( b \) is a constant (\( mL \ \mu g^{-1} \)). The slope and intercept of the linear plot of \( C_\text{e} / q_\text{e} \) versus \( C_\text{e} \) yield the values \( q_{\text{max}} \) and \( b \), respectively.

The equilibrium parameter (\( R_L \)) was used to evaluate the fundamental characteristics and practicability of the Langmuir isotherm.

\[
R_L = \frac{1}{1 + bC_0}
\]

where \( C_0 \) is the highest initial concentration of BCG (\( \mu g \ mL^{-1} \)) and \( b \) is the Langmuir constant. The value of \( R_L \) indicates the shape of the isotherm as follows: \( R_L > 1 \) (unfavorable), \( R_L = 1 \) (linear), and \( 0 < R_L < 1 \) (favorable).\(^{15,39}\)

The Freundlich isotherm is considered as model multilayer adsorption which occurs on a heterogeneous surface with uniform energy. It can be described as

\[
\log(q_\text{e}) = \frac{1}{n} \log(C_\text{e}) + \log k
\]

where \( k \) and \( n \) are the Freundlich constants, which represent the adsorption capacity of the adsorbent and the energy of adsorption, respectively. These values can be obtained from the intercept and slope of the linear plot of \( \log(q_\text{e}) \) versus \( \log(C_\text{e}) \).

The adsorption isotherms were fitted with Langmuir and Freundlich adsorption equations. The parameters are summarized in Table 3. The \( R^2 \) values obtained from both models also fit well with the Freundlich model. The \( 1/n \) value of 0.5686 obtained from the Freundlich isotherm indicated a moderate multilayer adsorption intensity of BCG over the heterogeneous surface of poly(GMA-MAA-EDMA)-CHT.

### 3.6. Thermodynamic Studies

To understand the influence of temperature on BCG adsorption with poly-(GMA-MAA-EDMA)-CHT, Gibbs free energy change (\( \Delta G^\circ \)), enthalpy change (\( \Delta H^\circ \)), and entropy change (\( \Delta S^\circ \)) were obtained by using the following equations:

\[
K_d = \frac{q_\text{e}}{C_\text{e}}
\]

\[
\Delta G^\circ = -RT \ln K_d
\]

\[
\ln K_d = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT}
\]

where \( K_d \) is the equilibrium constant, \( R \) is the ideal gas constant (8.314 \( J \ mol^{-1} K^{-1} \)), \( T \) is the temperature (K), and \( \Delta H^\circ \) and \( \Delta S^\circ \) were calculated from the slopes and intercepts of eq 10.

Figure 8 shows that the adsorption capacity of BCG onto poly(GMA-MAA-EDMA)-CHT increased with increase of temperature from 293.15 to 313.15 K. The thermodynamic parameters calculated are listed in Table 4. The negative values of \( \Delta G^\circ \) indicate that adsorption was a spontaneous process.

### Table 4. Thermodynamic Parameters for the Adsorption of BCG onto poly(GMA-MAA-EDMA)-CHT

| T/K | \( \Delta G^\circ /J mol^{-1} \) | \( \Delta H^\circ /J mol^{-1} \) | \( \Delta S^\circ /J mol^{-1} K^{-1} \) |
|-----|-----------------|-----------------|-----------------|
| 293 | \(-5.54 \pm 0.14\) | 18.96 \( \pm 0.15\) | 83.57 \( \pm 1.31\) |
| 303 | \(-6.14 \pm 0.22\) | 17.62 \( \pm 0.16\) | 86.14 \( \pm 1.31\) |
| 313 | \(-6.76 \pm 0.07\) | 16.28 \( \pm 0.15\) | 88.71 \( \pm 1.31\) |

The positive values of \( \Delta S^\circ \) imply that the adsorption of BCG on poly(GMA-MAA-EDMA)-CHT was an increasing random process. In addition, \( \Delta H^\circ \) values were positive, suggesting that the adsorption of BCG onto poly(GMA-MAA-EDMA)-CHT was endothermic.

### 3.7. Comparison of Poly(GMA-MAA-EDMA)-CHT Performance with the Other Absorbents

In Table 5, the maximum adsorption capacity of BCG with poly(GMA-MAA-EDMA)-CHT has been compared to that of other absorbents. In addition, Table 6 shows a comparison of the kinetic and isotherm model constants for BCG adsorption with other absorbents. It can be seen that poly(GMA-MAA-EDMA)-CHT has a relatively large adsorption capacity and short contact time for BCG, which is attributed to the composites structures and surface properties. The results showed that poly(GMA-MAA-EDMA)-CHT can be considered as a very effective adsorbent for the removal of BCG dyes.

### 3.8. Regeneration of Adsorbent

Regeneration of adsorbent for repeated reuse is one of the most important factors for performance evaluations. After the adsorption process is complete, the loaded poly(GMA-MAA-EDMA)-CHT was sequentially treated with NaOH (0.1 mol L\(^{-1}\)) and deionized water. Through these simple processes, the adsorbed BCG was washed out and poly(GMA-MAA-EDMA)-CHT was regenerated. The adsorption percentage of BCG with poly-(GMA-MAA-EDMA)-CHT remained above 97% after three times of recycling test (99.6% for \( n = 1 \), 99.9% for \( n = 2 \), and 97.9% for \( n = 3 \)). Results of the recovery tests indicated that poly(GMA-MAA-EDMA)-CHT can be employed as a kind of recyclable adsorbents for the adsorption of BCG.
The authors declare no competing financial interest.

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Table 5. Comparison of Maximum Adsorption Capacities with Various Adsorbents for BCG

| adsorbents          | dye   | adsorption capacity $q_{max}$ (mg g$^{-1}$) | adsorption time (min) | ref     |
|---------------------|-------|---------------------------------------------|-----------------------|---------|
| Ziziphus nummularia | BCG   | 19.61 mg g$^{-1}$                           | 8                     | 40      |
| modified PEPP       | BCG   | 52.63 mg g$^{-1}$                           | 90                    | 22      |
| CoFe2O4-NHS–250     | BCG   | 85.91 mg g$^{-1}$                           | 10                    | 41      |
| granite             | BCG   | 2.11 mg g$^{-1}$                            | 60                    | 5       |
| poly(GMA-MAA-EDMA)-CHT | BCG | 39.84 μg g$^{-1}$                          | 40                    | this study |

4. CONCLUSIONS

In the present study, poly(GMA-MAA-EDMA)-CHT was prepared and employed for adsorption of BCG from aqueous solution. Effects of pH and adsorption time were studied in batch experiments. Kinetics, adsorption isotherms, and thermodynamics were also examined. The kinetics study revealed that adsorption rate was high and fit a pseudo-second-order kinetic model. The Langmuir and Freundlich isotherm models for BCG onto poly(GMA-MAA-EDMA)-CHT were studied, and it was demonstrated that the Freundlich model fit the adsorption data better. Thermodynamic parameters suggested that the adsorption process was a spontaneous and endothermic one. Compared to other absorbents, poly(GMA-MAA-EDMA)-CHT has a relatively large adsorption capacity (39.84 μg mg$^{-1}$) and short contact time (40 min) for BCG. Furthermore, poly(GMA-MAA-EDMA)-CHT was sequentially treated with NaOH (0.1 mol L$^{-1}$) and deionized water for the goal of regeneration. The adsorption percentage of BCG with poly(GMA-MAA-EDMA)-CHT remained above 97% after three times of recycling test. Because of the high adsorption capacity, short equilibrium time, and easy recycling, poly(GMA-MAA-EDMA)-CHT has a potential for the adsorption of BCG in solutions.

| adsorbents          | pseudo-second-order model | Freundlich             |
|---------------------|---------------------------|------------------------|
|                     | $k_2$ (mg g$^{-1}$ min$^{-1}$) | $q_{max}$ (μg g$^{-1}$) | $R^2$ | $1/n$ | $k$ | $R^2$ | ref      |
| Ziziphus nummularia | 1.83                       | 6.25                   | 1.00  | 0.3236 | 4.074 | 0.989 | 40       |
| polymers            | 0.005                      | 36.76                  | 0.999 | 0.59   | 1.06  | 0.974 | 22       |
| Cd(OH)$_2$-NW-AC    | 0.0002                     | 103.09                 | 0.997 | 0.2362 | 60.09 | 0.855 | 1        |
| poly(GMA-MAA-EDMA)-CHT | 1.30                       | 2.48                   | 0.999 | 0.5686 | 5.0015 | 0.9932 | this study |

**Table 6. Comparison of Kinetic and Isotherm Model Constants for BCG Adsorption**
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