Biosorption of Congo Red from Aqueous Solutions Based on Self-Immobilized Mycelial Pellets: Kinetics, Isotherms, and Thermodynamic Studies

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ABSTRACT: In the current study, <i>Aspergillus fumigatus</i> and <i>Pseudomonas putida</i> were co-cultured to obtain self-immobilized mycelial pellets to evaluate the decolorization efficiency of Congo red (CR). The obtained co-culture exhibited the highest decolorization efficiency of 99.22% compared to monoculture of <i>A. fumigatus</i> (89.20%) and <i>P. putida</i> (55.04%). The morphology and surface properties of the mycelial pellets were characterized by SEM, FTIR, BET, and XPS. The adsorption kinetics and isotherms were well described by pseudo-second-order and Langmuir models. The findings revealed that the removal efficiency of the mycelial pellet for CR was significantly influenced by physico-chemical parameters. Thermodynamic result showed that the biosorption process was endothermic. The maximum adsorption capacity can be obtained from the Langmuir model, which is 316.46 mg/g, it suggests that mycelial pellet was an efficient biosorbent to remove CR from aqueous solution. This study indicates that the mycelial pellet can develop a sustainable approach to eliminate CR from the wastewater.

1. INTRODUCTION

Dye wastewater is one of the pollution sources of environmental water, which restricts the sustainable development of the printing and dyeing industry. Globally, dyes are annually produced with 700,000 tones yield, among which about 60% are azo dyes. Azo dyes and their degradation products contain azo functional groups (–N≡N–) and aromatic rings, which make them toxic (cytotoxic and genotoxic), carcinogenic, and difficult to biodegrade. In addition, dye-containing wastewater has become an important environmental problem due to its strong color, increased solid content, and poor biodegradability. The discharge of untreated dyes wastewater contaminate the surrounding environment as well as toxic for human beings and aquatic organisms. Therefore, dye removal is a challenging area in wastewater treatment. Several processes are used to remove dyes from dye-containing wastewater, such as ultrafiltration, electrochemical oxidation, chemical oxidation, electrochemical remediation, and by using biological sources, such as by using fungi, algae, bacteria, and plant. However, the chemical and physical processes of dye removal are associated with high cost, the low removal efficiency, poor regenerating capacity, and the generation of secondary pollution. Adsorption is a common and an effective method to remove dyes from industrial wastewater. Currently, many researches have focused on low-cost alternative materials to remove dyes by the adsorption method. Different kinds of adsorbents have been developed to remove dyes, like silica gel, activated carbons, cellulose fibers, nano metal oxides, and agricultural wastes. However, the adsorption capacity of the above adsorbent is not very high, hence, it is important to develop an adsorbent with high adsorption capacity, low cost, and easy availability. The microbial adsorbent has been proved to be one of the most promising dye adsorption methods. Currently, various types of fungal materials can be used as biosorbents to remove dyes from contaminated water, such as <i>Penicillium</i>, <i>Mucor circinelloides</i>, <i>Cladosporium sp.</i>, <i>Aspergillus oryzae</i>, <i>Fucus vesiculosus</i>, <i>Stenotrophomonas maltophilia</i>, and <i>Aspergillus nidulans</i>.

In this study, <i>Pseudomonas putida</i> was immobilized on <i>Aspergillus fumigatus</i>, forming novel biosorbent-immobilized...
mycelial pellets. This study was aimed, as follows: (i) to study the mycelial pellets as biosorbent to remove an anionic dye, Congo red (CR); (ii) to determine physicochemical parameters that affect adsorption (pH, contact time, temperature, initial dye concentration, shaking speeds, and salt concentrations); (iii) to determine the best-fit isotherm equation, according to Langmuir, Freundlich, Dubinin–Radushkevich, and Tempkin models; and (iv) to explain the nature of adsorption by kinetic and thermodynamic parameters.

2. RESULTS AND DISCUSSION

The co-culture resulted highest with 99.22% of decolorization at 100 mg/L of CR as compared to monocultures, 89.20% with AF, and 55.04% with PP. Therefore, in this study, the self-immobilized mycelial pellets formed by co-culture were used as the research object.

2.1. Characterization of Mycelial Pellets. 2.1.1. SEM.

The SEM images are shown in Figure 1. As is shown in the figure, the surface structure of mycelial pellets is porous; comparing the images of before dye biosorption and with those after dye biosorption, the pellet surface spaces are filled with the dye solution after dye sorption, the mycelial become thicker. This indicates that the dye molecule has a high affinity with the mycelial pellets. The possible reason is that the fungal cell wall contains polysaccharides, which makes the mycelium ball to have a strong biosorption capacity.

2.1.2. FTIR.

Due to the adsorption characteristics and adsorption capacity of the mycelial pellets, were affected by the surface functional groups. Figure 2. shows the FTIR of mycelial pellets before and after dye biosorption. The broad absorption peak at 3400–3700 cm$^{-1}$ was caused by the O–H stretching vibration of hydroxyl functional groups. There may be a NH$_2$ or C= N stretching (amides I and II), the spectrum existed two strong peaks in the regions of 1647.43 and 1543.02 cm$^{-1}$. In the spectrum of after biosorption, the peaks shifted to the regions of 1641.24 and 1549.21 cm$^{-1}$ and decreased compared to the before biosorption, indicating the interaction of the CR with the amide I and II functional.

Figure 1. SEM images of mycelial pellet before biosorption (a1, a2, and a3) and after biosorption (b1, b2, and b3) and magnification from 100 to 1000×.
groups. The peak at 1404.59 cm\(^{-1}\) may be caused by C–H bending, –CH\(_3\) stretching, or COO-symmetric stretching.\(^{18,28}\) The peak at 1237.55 and 1150.93 cm\(^{-1}\) was due to the C–N stretching (amide III). The peak showed at 821.48 and 781.26 cm\(^{-1}\) was attributed to the N–H bending. The peaks between 619.63 and 526.83 cm\(^{-1}\) represent aromatics.\(^4\) The absorption of CR by mycelial pellets caused an increase in peak intensity at 1237.55 and 1150.93 cm\(^{-1}\). The peaks at 821.48, 781.26, 619.63, and 526.83 cm\(^{-1}\) disappeared after CR biosorption. The new peaks appearing at 1450.99 and 1041.11 cm\(^{-1}\) may be because a new functional group is introduced on the surface of the mycelial pellet, which may be the reason for the adsorption of CR on the biosorbent.

2.1.3. Specific Surface Area and Pore Distribution. The BET method was used to determine the pore distribution of mycelial pellets. The N\(_2\) adsorption–desorption isotherms under low-temperature conditions are shown in the Figure 3. The surface area and total pore volume of the mycelial pellet were 5.12 m\(^2\)/g and 0.038 cm\(^3\)/g, respectively. The pores were mainly distributed in the range of 5–40 nm, with an average pore diameter of 15.01 nm, which indicated that the internal structure of the mycelial pellet was mainly mesopores. According to IUPAC, the adsorption process was similar to the type IV adsorption isotherm, the hysteresis loop of mycelial pellet belonged to the H3 type, which indicates that the mycelial pellet was formed by a loose flaky particle structure with slit holes.

2.1.4. XPS. XPS was used to further characterize the types of elements and functional groups on the surface of mycelial pellet. The XPS spectra before and after adsorption CR are shown in the figure. It can be seen from the wide-scan spectrum (Figure 4.) that the surface of the mycelial pellet mainly contains three elements, C, N, and O.

The O 1s spectra of mycelial pellets before and after adsorbed CR are shown in Figure 5a,b. The O 1s spectrum was fitted to three peaks (531.4, 532.7, and 533.4 eV), corresponding to C=O, O–C–N, and O==C–O, respectively.\(^{46}\) After biosorption, the content of C==O increased from 23.81 to 40.36%, while the content of O–C–N and O==C–O decreased, indicating that CR binds to the phenolic hydroxyl group on the surface of the mycelial pellet. The N 1s spectra are shown in Figure 5c,d. The spectra were deconvoluted with two peaks, 399.8 eV (\(−\)NH\(_2\)/\(−\)NH\(_−\)) and 401.6 eV (\(−\)NH\(_3^+\)/\(−\)NH\(_2^+\)).\(^{47}\) After CR adsorption, the content of \(−\)NH\(_2\) or \(−\)NH\(_−\) increased from 82.45 to 87.39%, which was due to the addition of the \(−\)NH\(_3^+\) of CR. The C 1s spectra of mycelial pellet before and after CR adsorption are presented in Figure 5e,f. Four peaks were observed at 284.6, 286.0, 287.5, and 288.6 eV, respectively, which can be assigned to C–C, C–O, O==C, and O==C–O.\(^{48}\) Comparing the C 1s before and after the adsorption of CR (Figure 4e,f), it can be seen that the content of C==O increased from 9.54 to 17.92%, which indicates that the C==O functional group was CR

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**Figure 2.** FTIR spectrum of mycelial pellet (a) before biosorption and (b) after biosorption.

**Figure 3.** (a) N\(_2\) adsorption–desorption isotherms; (b) BJH pore size distribution of mycelial pellet.

**Figure 4.** XPS survey spectra of mycelial pellet before and after CR adsorption.

**Figure 5.** Deconvoluted O 1s (a) before and after CR adsorption, (b) N 1s before and after CR adsorption, (c) C 1s before and after CR adsorption.
adsorption sites. The content of C–C decreased from 37.17 to 28.53%, it may be because CR can combine with O in the phenolic hydroxyl group, which reduces the charge density of O atoms and also reduces the charge density around C in C–O.49

2.2. Effect of Different Parameters on CR Adsorption.

2.2.1. Effect of pH. pH is one of the important factors in the CR biosorption process. The pH value not only affects the active sites on the surface of biosorption but also affects the properties of the dye. To study the effect of the solution pH on the mycelial pellet adsorption CR, the adsorption experiment was conducted at 100 mL of CR solution with a concentration of 100 mg/L at 30 °C and 160 rpm, pH ranged from 3 to 10. Figure 6a shows that the removal rate and biosorption capacity increased from pH 3.0 to pH 5.0, and reached the maximum at pH 5.0, which was decreased with the increase of pH. The amount of CR adsorption and the removal rate at pH 5.0 were 89.26 mg/g and 97.53%, respectively.

In acidic conditions, H+ is easily combined with the SO3− in CR, and the decolorization effect of the dye is increased by the electrostatic attraction between molecules (i.e., Dye-SO3Na – Dye-SO3− + Na+). However, when the pH of the solution was 3–5, the removal rate of CR increased with the increase of pH. The reason was that the color of CR solution changed and the absorbance decreased. Moreover, the activity of mycelial pellets was also one of the reasons that affect CR adsorption. The mycelial pellet activity reached the maximum at pH 5, higher or lower pH was bad for the adsorption of mycelial pellet. When the pH is >7, OH− is increased in the solution, the surface of fungal cell walls also contains a lot of negative charges; there was electrostatic repulsion between the mycelial pellet and CR,26 which lead to the decrease of the decolorization rate.

2.2.2. Effects of Contact Time. The adsorption of CR was affected by the contact time; the batch adsorption experiment was studied by adding 2 g of wet mycelial pellets to the 100 mL

![Figure 5](https://dx.doi.org/10.1021/acsomega.0c03114)  
Figure 5. (a, c, e) O 1s, N 1s, and C 1s of mycelial pellet before CR adsorption, (b, d, f) O 1s, N 1s, and C 1s of mycelial pellet after CR adsorption.
of 100–300 mg/L CR solution at pH 5.0. The contact time was set to 0–12 h to determine the optimal adsorption time. Obviously, Figure 6b shows the adsorption capability was increased with increasing contact time. The maximum adsorption capacity of mycelial pellets to CR at different concentrations was 60.15, 120.13, and 183.08 mg/g, respectively. This indicated that the dye can be freely adsorbed on the active site of the mycelial pellets, the adsorption amount increases rapidly, after that, the active site is occupied by the dye, and the adsorption capacity decreases.\(^{33}\)

2.2.3. Effects of Temperature. The effect of temperature was studied at temperatures of 20, 25, 30, 35, and 40 °C. As shown in Figure 6c, the temperature rose from 20 to 40 °C, the removal rate and biosorption amount of CR also increases with increasing temperature. Compared with 30 °C, the amount of adsorption remains unchanged, indicating that the biosorption process is endothermic.\(^{33}\) When the temperature increases from 25 to 40 °C, the amount of CR adsorbed by the mycelial pellets increases from 70.86 to 83.09 mg/g, and the removal rate of CR increases from 84.41 to 98.99%.

2.2.4. Effect of Initial Concentration. The effect of initial dye concentration on the removal rate and adsorption capacity was evaluated. The batch experiment was carried out at different initial CR concentrations from 50 to 500 mg/L at 30 °C, pH 5.0, and 160 rpm. It can be observed from Figure 6d that with increasing initial dye concentration, the biosorption capacity of CR on mycelial pellets increased from 30.52 to 182.36 mg/g, and the removal rate decreased from 99.49 to 46.24%. The limiting factor for dye biosorption may be owing to the occupation of adsorption sites on the biosorbent. At lower CR concentrations, the ratio of solute concentration to biosorption sites is higher, and the dye removal rate increases.

Figure 6. Effects of different parameters on the mycelial pellets biosorption of CR. (a) pH, (b) contact time, (c) temperature, (d) initial dye concentration, (e) rotational speed, and (f) NaCl concentration.
When the CR concentration increased, the adsorption efficiency decreased owing to the saturation of the adsorption sites on the surface of the adsorbent.  

2.2.5. Effects of Rotational Speed. The impact of rotation speed on adsorption of CR was conducted at pH 5.0, temperature of 30 °C, and 100 mL of 100 mg/L CR solution. Rotation speed was set from 0 to 200. As shown in Figure 6e, the biosorption capacity and removal rate were increased with the increase of the rotating speed and reached the maximum at 160 rpm. The removal rate of CR was only 57.55% under anaerobic conditions (rotation speed of 0 rpm), the adsorbed CR amounts and the removal rate at 160 rpm values were found to be 83.01 mg/g and 98.49%, respectively. The rotation speed beyond 160 rpm shows that the removal rate decreased, which may be due to the reduction of the membrane boundary layer around the pellets.  

2.2.6. Effects of Salt Concentrations. The influence of salt concentration on the biosorption capacity of mycelial pellets was studied at pH of 5.0, temperature of 30 °C, 160 rpm, and 100 mL of 100 mg/L CR solution, the NaCl concentration ranged from 0 to 100 g/L. Figure 6f shows that the removal rate and biosorption capability slightly decreased when the NaCl concentration was in the range of 0 to 40 g/L. It may be indicated that certain amount of NaCl is unfavorable for...
maintaining normal physiological activities of mycelial. Then, the NaCl concentration up to 40–100 g/L, the adsorption capacity remains stable. The result showed that the mycelial pellets had a strong tolerance to high salt concentration.

2.3. Biosorption Kinetics Study. To evaluate the adsorption mechanism of CR on the surface of mycelial pellets, pseudo-first-order, pseudo-second-order, Elovich, and intraparticle diffusion kinetic models were used to fit experimental data.

The linear equation of the kinetic models is given by following equations:

Pseudo-first-order model: \( \ln(q_e - q_t) = \ln q_e - k_1t \) 

Pseudo-second-order model: \( \frac{t}{q_t} = \frac{1}{k_2q_e^2} + \frac{t}{q_e} \)

Elovich model: \( q_t = \beta \ln(\alpha \beta) + \beta \ln t \)

Intraparticle diffusion model: \( q_t = k_i t^{0.5} + C \)

where \( q_t \) (mg/g) is the equilibrium adsorption capacity, \( q_e \) (mg/g) is the adsorption capacity at time \( t \), \( k_1 \) (1/h) is the adsorption rate constant of pseudo first-order kinetics, \( k_i \) (g/mg h) is the rate constant of pseudo second-order sorption, \( k_i \) (mg/g h0.5) is the rate constant of intraparticle diffusion, \( \alpha \) (mg/g/h) is the initial adsorption rate, and \( \beta \) (g/mg) is the desorption constant.

Figure 7 shows the plot of kinetic models at different initial CR concentrations. The kinetic parameters were shown in Table 1. Based on the analyses of the \( R^2 \), the pseudo-second-order kinetic model has a higher \( R^2 \) value (average value, 0.9905), which can better fit the experimental data \( (q_{exp}) \), and the calculated values \( (q_{cal}) \) and \( q_{exp} \) are closed to. This result indicates that the adsorption of CR dye on mycelial pellets follows the pseudo-second-order kinetic model. From the Table 1, the \( R^2 \) value of the Elovich model is 0.9577 (average value), the better fitting results indicate that CR biosorption by mycelial pellet can be considered as a chemisorption process. However, \( R^2 \) cannot fit well at all concentrations, wherefore the adsorption of CR is not only chemisorption. The diffusion mechanism can be confirmed by the intraparticle diffusion model, which consists of three linear parts: film diffusion, pore diffusion, and adsorption equilibrium. The \( k_i \) values can be obtained from the slope of the straight line \( t^{0.5} \) vs \( q_t \). The experimental result shows that the \( k_i \) values increase with increasing dye concentration, it may be due to the higher CR concentration, the stronger adsorption force. As shown in Figure 7d, the straight lines do not pass through the origin, which indicates that the mycelial pellets adsorption process of CR is controlled by intraparticle diffusion and boundary layer diffusion, and intraparticle diffusion is not the only rate control step.

2.4. Biosorption Isotherms Study. Adsorption isotherm was estimated to describe the interaction between CR and mycelial pellet. Four isotherm models of Langmuir, Freundlich, Tempkin, and Dubinin–Radushkevich (D–R) were used to calculate the isotherm parameters and maximum adsorption capacity. Isotherms adsorption experiments were conducted at CR concentrations in the range of 50 to 400 mg/L.

The mathematical expressions for the isotherm models are expressed as follows:

Langmuir Isotherm model: \( \frac{q_e}{q_m} = \frac{q_e}{q_m} + \frac{1}{K_q q_m} \)

Freundlich Isotherm model: \( \ln q_e = \ln K_f + \frac{1}{n} \ln q_e \)

Tempkin model: \( q_e = B \ln A + B \ln c_e = \frac{RT}{Z} \)

Dubinin–Radushkevich model (D–R): \( q_e = \ln q_e - BA^2 \)

where \( q_e \) (mg/L) is the equilibrium CR concentration (mg/L), \( q_e \) (mg/g) is equilibrium adsorption amount. \( q_m \) is the maximum monolayer adsorption capacity (mg/g). \( K_q \) and \( K_f \) are the Freundlich and Langmuir constant (mg/L), respectively. \( A \) and \( B \) are Tempkin constants, \( R \) and \( T \) are the universal gas constant and absolute temperature (K), respectively, and \( Z \) is the Temkin isotherm adsorption heat (J/mol). In the D–R isotherm, \( B \) is the D–R adsorption isotherm constant, mol2/J2; \( A \) is the Polanic adsorption potential energy, J/mol; and \( q_e \) (mg/g) is the theoretical saturation capacity.

The parameters of the isotherm model are listed in Table 2. The plots of isotherm models for the adsorption of CR were presented in Figure 8. According to the \( R^2 \) value, the Langmuir isotherm model was better fitted with the biosorption of CR on mycelial pellet than the Freundlich, Tempkin, and D–R isotherm models with the \( R^2 \) value of 0.99295. This result indicated that the CR biosorption on mycelial pellet was a monolayer adsorption. Contrary to Langmuir, the Freundlich model can be described in the multilayer adsorption of CR with heterogeneous energy distribution biosorption active sites. The value of the Freundlich constant \( n \) was 1.754 for mycelial pellets, indicating that CR was favorably biosorbed by mycelial pellets and it had a good affinity for CR. The maximum adsorption capacity of the mycelial pellet obtained from the Langmuir isotherm model was 316.46 mg/g. The indirect interaction between CR and mycelial pellets and the enthalpy of the adsorption process can be described by the Temkin model. The calculated Z value was positive 43.88 J/mol.
mol\(^{-1}\), which indicated that the biosorption process of CR was endothermic in nature. Moreover, adsorption free energy (\(E\)) can be obtained from the D–R model, the adsorption mechanism can be explained by \(E\) value. If the value of \(E\) is <8 kJ/mol, the process is controlled by physical biosorption, the value of \(E\) is 8–16 kJ/mol, indicating that the adsorption process is ion exchange, while its value within the range of 20–40 kJ/mol indicates chemisorption.\(^{41}\) For biosorption of CR by mycelial pellets, the \(E\) value was found to be 1.866 kJ/mol. Therefore, the biosorption of CR was physical mechanisms.

2.5. Adsorption Mechanism. Based on adsorption kinetics and adsorption isotherm analysis and characterization results, the adsorption of CR by mycelial pellets was a combination of physical adsorption and chemical adsorption, and physical adsorption plays a main role in the adsorption process of CR.

The adsorption mechanism of CR can be explained from three aspects (Figure 9). (1) The pore structure of mycelium pellets provided abundant adsorption sites for CR adsorption. (2) The fungal cell wall contains abundant chemical groups, such as hydroxyl, carboxyl, and amide groups. Therefore, CR can be interacted with the hydroxyl group on the surface of the mycelial pellet through the H-bond. (3) Electrostatic interaction played an important role in the CR adsorption process. The electrostatic interaction between the protonated amino groups on the mycelial pellet and the \(\text{SO}_4^{2-}\) plays a major role in the adsorption of CR. In addition, the protonated amino group in the structure of CR and the protonated amino group on the surface of the mycelial pellet produce repulsion.\(^{51,52}\)

2.6. Adsorption Thermodynamics Study. Thermodynamic experiments were carried out to explain the nature of biosorption process. The thermodynamic parameters of the adsorption process of CR were determined at pH 5.0, 160 rpm, and 100 mL of 100 mg/L CR solution. The adsorption temperatures ranged from 25 to 40 °C. The following equations were used to estimate the thermodynamic parameters, standard free energy change (\(\Delta G\)), enthalpy change (\(\Delta H\)), and entropy change (\(\Delta S\)).\(^{30}\)

\[
\Delta G = -RT \ln K
\]
\[
\ln K = \frac{\Delta S}{R} - \frac{\Delta H}{RT}
\]
The estimated thermodynamic parameters were shown in Table 3. The values of \( \Delta H \) and \( \Delta S \) were obtained from slope and intercept of \( \ln K \) vs \( 1/T \). The \( \Delta G \) value decreased with increasing temperature, negative values suggested the spontaneous nature of CR adsorption on mycelial pellets and the feasibility of the method. It was observed that \( \Delta S \) and \( \Delta H \) values were 0.956 kJ/mol-k and 251.667 J/mol, respectively, which indicated that the degree of freedom of adsorption of CR on the mycelial pellets and the process was endothermic. Therefore, according to the thermodynamic function relationship, the calculated thermodynamic parameters \( \Delta H > 0, \Delta S > 0, \Delta G < 0 \) of the adsorption process indicate that the adsorption of CR by the mycelial pellets is a spontaneous and an endothermic process within the temperature range of the experimental study. Increasing temperature facilitates the adsorption process.

2.7. Reusability and Desorption Study. It is important for adsorbent to have the recycling and regeneration capacity. Adsorbents with high adsorption capacity and desorption property are considered cost effective. Figure 10a shows that the mycelial pellet is highly reusable. In the first cycle, 97.63% decolorization was obtained within 12 h. After the 8th cycle, the mycelial pellets retained 85.34% removal rate and 69.86 mg/g biosorption ability.

Figure 10b shows the adsorption efficiency of CR on mycelial pellets after treatment with different desorption eluents. The results show that the ethanol eluent can effectively desorb of CR from adsorbent material. 0.1 M HCl and acetic acid showed lower desorption but 0.1 M NaOH and acetone desorb about 20.53 and 42.36% CR from mycelial pellets, respectively. Low desorption efficiency in acidic solution indicates that CR was firmly attached to the mycelial pellets by chemisorptions.

2.8. Comparison of Different Adsorbents. As shown in Table 4, compared with other reported adsorbents, the mycelial pellet have excellent adsorption capacity to remove CR from wastewater.

3. CONCLUSIONS

The mycelial pellets can be used as an effective adsorbent for the removal of CR from aqueous solutions under the optimum conditions (i.e., pH 5.0, temperature of 30 °C, shaking speed of 160 rpm, and the adsorbent dose of 2 g/100 mL). The results of SEM, FTIR, BET, and XPS showed that the surface of mycelial pellet had functional groups and was a porous structure, which was beneficial to the combination of CR. The Langmuir isotherm and pseudo-second-order kinetic models are found to fit the experimental data best. Furthermore, the value of \( \Delta H \) revealed that the biosorption process is endothermic. Adsorbent maintains high adsorption capacity after eight reuses. Thus, mycelial pellets could be used as eco-friendly biosorbent to remove CR in terms of short adsorption time, high biosorption capacity, and reusability, moreover, it also the main advantages of the mycelial pellets as a biosorbent for low cost, easy to obtain and separation after biosorption.

4. MATERIALS AND METHODS

4.1. Microorganisms and Materials. A. fumigates (Gen bank no. MG183670) used in this study was isolated from the virgin forest soil taken from Xing Long Mountain in northwest...
The percentage removal of CR (% removal) and adsorption capacity 
$q_\text{i} (\text{mg/g})$ were calculated by the eq 12 and 13.\(^{30}\)

\[
\text{% removal} = \frac{C_0 - C_\text{f}}{C_0} \times 100
\]

\[
q_\text{i} = \frac{(C_0 - C_\text{f}) \times V}{W}
\]

where $C_0$ (mg/L) and $C_\text{f}$ (mg/L) are the initial CR concentration and CR concentration of solution at a time $t$, $V$ (L) is the volume of CR solution and $W$ (g) is the dry weight of mycelial pellets used.

4.5. Reusability and Desorption Study. To evaluate the reusability of the mycelial pellet, 2 g of the mycelial pellet was added to a 250 mL Erlenmeyer flask containing 100 mL of 100 mg/L CR solution for decolorization for 12 h. Subsequently, we collect the mycelial pellets by filtration and transfer them to a fresh CR solution to carry out the decolorization experiment. Each decolorization without desorption and repeat the same procedure 7 times.

For desorption study, 2 g mycelial pellets were used to adsorb CR concentration of 50 mg/L. After biosorption, the adsorbent was washed with distilled water to remove unadsorbed dye. Subsequently, the biosorbent was transferred into 50 mL solutions containing 0.1 M NaOH, 0.1 M HCl, ethanol, acetic acid, and acetone solution, shaking at 30 °C for 12 h. The desorption efficiency was estimated using eq 14.\(^{31}\)

\[
E_d(\%) = \frac{Q_d}{Q_e} \times 100
\]

where $Q_d$ and $Q_e$ are the amount of dye desorbed (mg) and dye absorbed (mg), respectively.

4.6. Characterizations. The surface morphology and functional groups of mycelial pellets were investigated by SEM, FT-IR, BET, and XPS.

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**Notes**

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