Adsorptive removal of anionic dyes from aqueous solutions using spent mushroom waste

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Abstract
The removal of hazardous dyes has become a major economic and health concern to treat wastewater. In this study, efficient, low-cost, and eco-friendly spent mushroom waste (SMW) showed great potential for removing the anionic dyes, namely Direct Red 5B (DR5B), Direct Black 22 (DB22), Direct Black 71 (DB71), and Reactive Black 5 (RB5). The mechanisms of adsorption could be controlled by both physical and chemical adsorption. Scanning electron microscope analysis showed that SMW surface is porous and irregular. The kinetic study could be described well with the pseudo-second-order kinetic model, whereas the best representation of the equilibrium isotherm is the Langmuir model. The maximum adsorption capacities of SMW were found to be 18 mg g\(^{-1}\) for DR5B, 15.46 mg g\(^{-1}\) for DB22, 20.19 mg g\(^{-1}\) for DB71, and 14.62 mg g\(^{-1}\) for RB5. The analysis of thermodynamic study of Δ\(^{\Delta G^o}\), Δ\(^{\Delta H^o}\), and Δ\(^{\Delta S^o}\) proved that the adsorption of the tested dyes onto SMW was endothermic and spontaneous. Based on these results, SMW can be considered as high potential adsorbent for the removal of dyes from wastewater.

Keywords Adsorption · Spent mushroom waste · Dye removal · Kinetics · Isotherm · Thermodynamics

Introduction
In recent decades, rapid industrialization and urbanization have caused a disturbing global increase in water pollution. Pollutants of the greatest environmental concern are heavy metals, organic dyes, and pharmaceuticals. Large quantities of dyes, some of which are carcinogenic, mutagenic, and toxic to aquatic life (Yagub et al. 2014), are being continuously discharged from textile, paper, cosmetics, food, and leather industries (Chatterjee et al. 2011). To preserve the water quality, it is of utmost importance to treat the dye-containing effluents effectively before they get discharged into the environment.

Dyes can be classified into cationic (basic dyes), anionic (reactive, acid, or direct dyes), and nonionic (dispersive dyes) (Yagub et al. 2014). Anionic dyes, which contain negatively charged sulfonic groups (SO\(^3^-\)), are highly soluble and visible in water bodies (Liu et al. 2014). They can be successfully removed from wastewater by conventionally available techniques, such as nanofiltration (Liu et al. 2017), ozonation (Rodríguez et al. 2017), flocculation (Xiao et al. 2017), oxidation (Soares et al. 2017), photo-degradation (Fahimirad et al. 2017), membrane separation (Ciardelli et al. 2001), microbial degradation (Kadam et al. 2013), and coagulation (Nourmoradi et al. 2015). However, several of these techniques have limited applicability because of the high cost, generation of secondary pollution, or complex reaction conditions. One of the methods with fewer limitations is adsorption, which is cost-effective, highly efficient, easy to operate, and does not cause secondary pollution. Some cost-effective organic adsorbents include peat (Allen et al. 2004), grapefruit peels (Saeed et al. 2010), rice husk (Han et al. 2008), peanut husk (Sadaf and Bhatti 2014), banana peels (Munagapati et al. 2018), wood apple shells
An alternative organic material that can be used as a dye adsorbent is spent mushroom waste (SMW), residual waste left after mushroom harvest. For every kilogram of mushrooms produced, there is 5 kg of leftover SMW (Medina et al. 2012). In China, the largest global producer of mushrooms, such large amounts of SMW lead to considerable pollution. The problem of SMW disposal can be solved by biodegradation (Li et al. 2010) or utilizing SMW as animal feed (Fazaeli et al. 2014), energy source (Finney et al. 2009), or a fertilizer (Lou et al. 2017). However, being rich in natural biopolymers, including chitin, chitosan, cellulose, hemicelluloses, and proteins, SMW is also a promising adsorbent material. Its biopolymers contain functional groups such as hydroxyl, carboxyl, and amide, which provide binding sites for water pollutants. To the best of our knowledge, only a few studies have so far considered using SMW as an adsorbent for the removal of Basic Red 18 and Acid Red 111, Congo Red dyes (Tian et al. 2011), and heavy metals (Molaheid et al. 2019) from aqueous solutions.

The aim of the current work was to study the potential of SMW as an alternative adsorbent for the removal of toxic dyes from aqueous solutions. The influence of different parameters, for example contact time, pH solution, adsorbent dosage, initial dye concentration and temperature, was evaluated in a batch experiment. The kinetic study was fitted by different models, namely pseudo-first-order, pseudo-second-order, and Elovich models, whereas the equilibrium data were fitted to different isotherm models including Langmuir, Freundlich, Dubinin–Radushkevich, and Redlich–Peterson. Thermodynamic parameters were investigated to determine the feasibility and spontaneity of the adsorption process. Finally, SMW was sampled before and after dye adsorption, and the details of its surface morphology and composition were inspected by Fourier transform infrared (FTIR) spectroscopy and field emission scanning electron microscopy (FE-SEM).

### Materials and methods

#### Chemicals

Direct Black 22 (DB22), Direct Red 5B (DR5B), Reactive Black 5 (RB5), Direct Blue 71 (DB71) (Fig. S1), sodium hydroxide (NaOH), and hydrochloric acid (HCl) were all of the analytical grade and obtained from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China). Deionized water was used to dilute the chemicals throughout the experiments. The Huazhong Agricultural University (Wuhan, China) provided us with the SMW of oyster mushrooms (*Pleurotus ostreatus*).

#### Preparation of dye solutions

The stock solutions of the DR5B, DB22, DB71, and RB5 were prepared at a final concentration of 1 g L\(^{-1}\) and diluted as necessary. The concentrations of test dye solutions were determined with the help of calibration curves constructed using standards of different concentrations.

#### Preparation and characterization of spent mushroom waste

SMW was repeatedly washed with deionized water to eliminate the dirt from the surface and then dried in an oven at 100 °C for 6 h. The dried SMW was crushed into powder using a blender and then sieved into particles smaller than 0.4 mm. The powder was again repeatedly washed with deionized water, oven-dried at 100 °C for 10 h, and stored in glass bottles until further use. To characterize SMW before and after the adsorption, FTIR spectroscopy of the samples was performed in the range of 4000–400 cm\(^{-1}\) (Thermo Fisher Scientific, Waltham, USA) using a KBr pellet (IR grade, Bruker, Germany). The SMW surface morphology before and after the adsorption was studied using a scanning electron microscopy (SEM) (Philips XL30, Eindhoven, the Netherlands).

#### Batch experiments with spent mushroom waste

To evaluate the effects of different adsorption parameters, including temperature, pH, contact time, adsorbent dosage, and initial dye concentration, batch adsorption experiments were conducted in centrifuge tubes containing 50 mL of the dye solutions. The influence of pH was assessed in the range of 2–10, which was adjusted using 0.01 M HCl and/or 0.01 M NaOH solutions. The influence of adsorbent dosage was studied by adding varying amounts of SMW (0.4–1.5 g) to the solutions of DR5B, DB22, DB71, and RB5. The influence of initial concentrations on the equilibrium in the range of 100–1300 mg g\(^{-1}\) was investigated. The samples of SMW were withdrawn immediately after the adsorption and filtered using syringe nylon membrane filters with a pore size of 0.22 μm (GE nylon membrane, Pittsburgh, PA). The remaining solutions were measured using UV spectroscopy (Shimadzu, Kyoto, Japan) at a maximum wavelength of 540 nm for DR5B, 474 nm for DB22, 587 nm for DB71, and 590 nm for RB5. All batch experiments were done in triplicate, and adsorption capacity of SMW(mg g\(^{-1}\)) were computed according to Eq. (1):

\[
\text{Adsorption capacity (mg g}^{-1}\text{)} = \frac{(C_0 - C_e)V}{m}
\]
where \( C_0 \) (mg g\(^{-1}\)) is the initial dye concentration, \( C_e \) (mg g\(^{-1}\)) is the equilibrium dye concentration, \( V \) (L) is the volume of the dye solution, and \( m \) is the adsorbent mass (g). The removal efficacy (%) was calculated according to Eq. (2):

\[
\text{Removal efficacy (\%)} = \frac{C_0 - C_e}{C_0} \times 100
\]  

Modeling studies

**Adsorption kinetics** For the study of adsorption kinetics, 1 g of SMW was added into 50-mL tube containing 200 mg g\(^{-1}\) solutions of DR5B, DB22, DB71, and RB5 for 240 min at 25 °C. The solutions were sampled at different time points from 0 to 420 min to evaluate the residual dye concentrations. The measured values were fitted with the pseudo-second-order, pseudo-first-order, Elovich, and intraparticle diffusion models according to Eqs. (3–6): \( q_t \) (mg g\(^{-1}\)) is the amount of dyes adsorbed onto SMW, \( k_f \) (min\(^{-1}\)) is the rate constant of the pseudo-first-order kinetic model, \( k_s \) (g mg\(^{-1}\) min\(^{-1}\)) is the rate constant of the pseudo-second-order kinetic model, \( \alpha \) (mg g\(^{-1}\) min\(^{-1}\)) is the initial adsorption rate, \( \beta \) (g mg\(^{-1}\)) is the constant related to the activation energy and the extent of surface coverage, and \( k_e \) (g mg\(^{-1}\) min\(^{-1}\)) is the intraparticle diffusion model constant.

**Adsorption isotherms** The adsorption isotherm is the essential information needed to understand the interactions between dyes and adsorbents (Mahmoud et al. 2016). The adsorption isotherm study was conducted at initial dye concentrations of 100–1300 mg g\(^{-1}\). The dye solutions were mixed with SMW by agitation in the shaker for 240 min at 180 rpm and 25 °C, and the residual dye concentrations were determined after membrane filtration. To evaluate the most appropriate dye adsorption isotherm, the equilibrium data were fitted to the Langmuir, Freundlich, Redlich–Peterson, and Dubinin–Radushkevich isotherms models according to Eqs. (7–12):

\[
q_e = \frac{q_mK_aC_e}{1 + K_aC_e}
\]  

\[
q_e = K_nC_e^{1/n}
\]  

\[
q_e = \frac{K_rC_e}{1 + a_rC_e}
\]  

\[
\alpha_e = q_m \exp\left(-\frac{B\epsilon^2}{T}\right)
\]  

\[
\epsilon = RT \ln \left(1 + \frac{1}{C_e}\right)
\]  

\[
E = \frac{1}{\sqrt{2\beta_d}}
\]  

where \( q_m \) (mg g\(^{-1}\)) is the determining the maximum adsorption capacities of a saturated monolayer on the adsorbent’s surface; \( K_a \) (L mg\(^{-1}\)) is the rate constant of the Langmuir model; \( K_n \) ((mg g\(^{-1}\))/(L mg\(^{-1}\))\(^{1/n}\)) is the rate constant of the Freundlich model; \( K_r \) (L g\(^{-1}\)) and \( a_r \) (L mg\(^{-1}\)/L g\(^{-1}\)) are the constants of the Redlich–Peterson model; \( g \) is the interpreter of the Redlich–Peterson isotherm with a value between 1 and 0; \( B \) (mol\(^2\) kJ\(^{-2}\)) is the rate constant of the Dubinin–Radushkevich isotherm; \( \epsilon \) (KJ mol\(^{-2}\)) is the Polanyi potential related to adsorption energy; \( R \) (8.314 J mol\(^{-1}\) K\(^{-1}\)) is the ideal gas constant; \( T \) (K) is the temperature in Kelvin; and \( E \) (kJ mol\(^{-1}\)) is the adsorption process energy.

**Thermodynamic analysis**

The thermodynamic analysis was conducted to test whether the adsorption of DR5B, DB22, DB71, and RB5 onto SMW is a spontaneous process and to uncover its mechanism (Ara-vindhan et al. 2007). Different thermodynamic variables, including free energy change (\( \Delta G^\circ \)), enthalpy (\( \Delta H^\circ \)), and entropy (\( \Delta S^\circ \)), were computed using the following equations (Rathod et al. 2014):

\[
K_d = \frac{C_{ad,e}}{C_e}
\]  

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

\[
\ln(K_d) = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT}
\]
where $K_d$ is the distribution coefficient at the equilibrium, $C_{ad,e}$ (mg L$^{-1}$) are the equilibrium concentration of adsorbate, and $T$ is absolute temperature (K). The values of $\Delta G^\circ$ are calculated from Eq. (14).

Results and discussion

The effect of pH

Solution pH has a considerable effect on surface charge by causing the adsorbent to ionize and functional groups in the adsorbents active sites to dissociate in the solution (Wawrzikiewicz and Hubicki 2009). The influence of solution pH on the adsorption process of DR5B, DB22, DB71, and RB5 onto SMW was examined in the pH range of 2–10. Figure 1 demonstrates that the adsorption of anionic dyes was the highest at pH 2.0 (95% for DR5B, 98% for DB22, 95% for DB71, and 96% for RB5) and then decreased with a rise in pH from 3 to 10. This was due to the dissociation of anionic dyes in an aqueous solution:

\[
\text{Dye} + \text{SO}_4\text{Na} + \text{H}_2\text{O} \rightarrow \text{Dye} + \text{SO}_4^- + \text{Na}^+ + \text{H}_3\text{O}^+
\]

In acidic solutions, the adsorbent surface is positively charged, which is beneficial to the adsorption of anionic dyes due to the increased electrostatic interactions between the positively charged adsorbent’s surface and negatively charged $\text{SO}_3^-$ group of dyes. In alkaline solutions, anionic dyes compete with excess $\text{OH}^-$ ions in the solution, which leads to a decrease in the number of positively charged functional groups on the adsorbent’s surface. This results in repulsive electrostatic forces between the adsorbent’s surface and anionic dyes and, consequently, lower removal efficiency (Un and Ates 2019). Accordingly, the adsorptive removal of dyes was also lower at higher pH in this study. Several researchers who studied the relationship between pH and the adsorptive removal of anionic dyes by various adsorbents found that the adsorption reached its peak at low pH values (Munagapati et al. 2018; Samarghandy et al. 2011; Un and Ates 2019).

The influence of adsorbent dosage

The dye removal efficiency is greatly affected by the adsorbent dosage. According to Fig. 2, the removal efficiency increased to 100% from 32% for DR5B, 35% for DB22, 31% for DB71, and 44% for RB5 with an increase in the amount of adsorbent from 8 to 30 g L$^{-1}$. Increased dye removal efficiency could be ascribed to the increased number of available sites on the adsorbent’s surface with an increase in its dosage.

The influence of contact time

As demonstrated in Fig. S2, the influence of contact time on the adsorption capacities of DR5B, DB22, DB71, and RB5 was examined at different initial dye concentrations (50–200 g L$^{-1}$). The dye adsorption of all studied dyes rapidly increased from 0 to 60 min and then gradually continued to increase until 240 min, when the maximum adsorption was reached. This stabilization of the adsorption value indicates that the equilibrium was reached. At the beginning, there were numerous unoccupied adsorption sites on the adsorbent’s surface, and the adsorbate concentration was high. When only a few active sites remained available for the adsorption, the process reached the plateau phase.
The influence of initial dye concentration

The relationship between the initial concentration of DR5B, DB22, DB71, and RB5 and the adsorption onto SMW is present in Fig. S3. When the initial concentration of dyes increased from 100 to 1300 mg g\(^{-1}\), the adsorption capacity increased until it reached a plateau, which was at 16 mg g\(^{-1}\) for DR5B, 14 mg g\(^{-1}\) for DB22, 18 mg g\(^{-1}\) for DB71, and 13 mg g\(^{-1}\) for RB5. A similar result was observed for Congo Red on calcium-rich fly ash and also Basic Green 4 on olive pomace (Acemioğlu 2004; Koçer and Acemioğlu 2016). This may be ascribed to an increased bulk flow of the dyes toward SMW, which causes an increase in the available number of binding sites on the SMW surface.

Modeling studies

Adsorption kinetics The information on the adsorption kinetics is important for gaining insight into the adsorption process and successful design of the adsorption system. As shown in Fig. 3, the experimental data on the adsorption of DR5B, DB22, DB71, and RB5 were tested using the pseudo-first order, pseudo-second-order, and Elovich models. The modeling results are presented in Tables S1 and S2. The low values of correlation coefficients (\(R^2\)) for the pseudo-first-order show that it poorly fitted the experimental data on the tested dyes. On the other hand, the pseudo-second-order model yielded the highest \(R^2\) values of all tested models. In addition, the \(q_{e, \text{col}}\) value calculated for this model was very similar to the experimental \(q_e\) value. Hence, the pseudo-second order was found to best describe the adsorp-

![Fig. 3 Kinetic models of the adsorption of DR5B (a), DB22 (b), DB71 (c), and (d) RB5 onto spent mushroom waste](image-url)
tion of DR5B, DB22, DB71, and RB5 onto SMW, which indicates chemisorption (Hameed et al. 2008).

In intraparticle diffusion model, the $q_t$ versus $t^{1/2}$ was plotted and is shown in Fig. 4. The result shows that all dye concentration did not pass through the origin, indicating that the intraparticle diffusion was not the only rate-limiting step and the adsorption was controlled by other mechanism (Jain and Gogate 2017; Lafi and Hafiane 2016). Figure 4 shows that the intraparticle diffusion plot in current study shows three portions. The initial portion shows faster diffusion of dye through the boundary layer of solution to the external surface of SMW. The second portion involves gradual adsorption, where adsorption mechanism of intraparticle diffusion is a rate-determining step (Lafi and Hafiane 2016). The third portion is the final equilibrium stage, where intraparticle diffusion slows down relatively low residual concentration of the dye in the solution (Wang et al. 2008). The values of slope $K_{e1}$ and intercept $C_1$ for all portions are shown in Table S1 and S2. The values of constant of $K_e$ increased with the increase in dye concentration from 50 to 100 mg.L, due to enhanced driving force available at higher dye concentrations (Albadarin et al. 2017). The $C_{1,2,3}$ value can be an estimation of the thickness of the boundary layer (the large $C$ value indicates a great boundary layer effect) (Kannan and Sundaram 2001). From Table S1 and S2, the value of $C_{1,2,3}$ for all the concentration in all portions is found to increase with the increase in concentration, which implies that the thickness of the boundary layer increases as the initial concentration increases.

Fig. 4 Intraparticle diffusion model of the adsorption of DR5B (a), DB22 (b), DB71 (c), and (d) RB5 onto spent mushroom waste
Adsorption isotherms The adsorption isotherm is one of the critical means to understand the dye adsorption mechanism. To determine the adsorption mechanism as well as the maximum adsorption capacity, the experimental data were tested with the most common adsorption isotherm models, namely Langmuir, Freundlich, Dubinin–Radushkevich, and Redlich–Peterson (Fig. 5). The evaluation parameters for isotherms together with correlation coefficients from the plots are given in Table 1. Based on the $R^2$ values, the Langmuir isotherm model was found to be the best fit for the adsorption of DR5B, DB22, DB71, and RB5 onto SMW. According to this model, the maximum monolayer adsorption capacities of SMW were estimated to be 18 mg g$^{-1}$ for DR5B, 15.46 mg g$^{-1}$ for DB22, 20.19 mg g$^{-1}$ for DB71, and 14.62 mg g$^{-1}$ for RB5.

In addition, the Dubinin–Radushkevich model allows us to determine the free energy of adsorption, which gives us information on whether the processes are physisorption or chemisorption. The values of free energy ($E$) were thus calculated to be 16.57 kJ mol$^{-1}$ for DR5B, 18.56 kJ mol$^{-1}$ for DB22, 17.67 kJ mol$^{-1}$ for DB71, and 16.22 kJ mol$^{-1}$ for RB5, suggesting that the adsorption of these dyes was physisorption (Chabani et al. 2006). Additionally, the Redlich–Peterson isotherm model was compared to the Freundlich and Langmuir isotherms. The Redlich–Peterson isotherm turned out to be preferable to the Langmuir or Freundlich models (Kale et al. 2019). As shown in Table 1, the value of $g$ was approximately 1, which indicates homogeneity and approximates the Langmuir equation more than the Freundlich equation.
Comparing the removal of dyes by different adsorbents The maximum adsorption capacity values of SMW for DR5B, DB22, DB71, and RB5 determined in this study were compared with the literature values for other adsorbents. As given in Table 2, the SMW has an excellent potential to remove DR5B, DB22, DB71, and RB5 from aqueous solutions.

Thermodynamic analysis

A graph plotting the ln$K_d$ values versus temperature is shown in Fig. 6. The values of $\Delta G^\circ$, $\Delta H^\circ$, and $\Delta S^\circ$ at different temperatures are shown in Table 3. As demonstrated by the negative values of $\Delta G^\circ$, the adsorption of DR5B, DB22, DB71, and RB5 onto SMW was feasible and spontaneous. The diminishing magnitude of $\Delta G^\circ$ at higher temperatures also points to the spontaneity of the process. Therefore, the negative values of $\Delta G^\circ$ in the range of $-20$ to $0$ kJ mol$^{-1}$ are suggestive of physisorption, whereas the more negative values of $\Delta G^\circ$ in the range of $-80$ to $-400$ kJ mol$^{-1}$ suggest that

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**Table 1** Isotherm parameters for the adsorption of DR5B, DB22, DB71, and RB5 onto SMW

|        | DR5B | DB22 | DB71 | RB5 | DR5B | DB22 | DB71 | RB5 |
|--------|------|------|------|------|------|------|------|------|
|        |      |      |      |      |      |      |      |      |
|        |      |      |      |      |      |      |      |      |
|        |      |      |      |      |      |      |      |      |
|        |      |      |      |      |      |      |      |      |
|        |      |      |      |      |      |      |      |      |

**Table 2** Comparison of SMW’s adsorption capacity for anionic dyes with the values of other adsorbents

| Adsorbent       | Adsorbate      | $Q_m$ (mg g$^{-1}$) | References                      |
|-----------------|----------------|---------------------|---------------------------------|
| Fly ash         | Reactive Black 5 | 4.38                | Pengthamkeerati et al. (2008)   |
|                 | Reactive Red 23  | 2.10                | Sun et al. (2010)               |
| Peanut hull      | Reactive Black 5 | 5.55                | Tanyildizi, (2011)              |
| Peanut hull      | Reactive Black 5 | 5.55                | Tanyildizi, (2011)              |
| Peanut hull      | Reactive Blue 21 | 66.67               | Demirbas and Nas (2009)         |
| Ackee apple      | Congo Red       | 161.89              | Bello et al. (2013)             |
| Zeolite          | Reactive Blue 21 | 66.67               | Demirbas and Nas (2009)         |
| High lime fly ash| Reactive Black 5 | 7.18                | Eren and Acar (2007)            |
| Macadamia seed husks | Reactive Black 5 | 1.1436              | Felista et al. (2020)           |
| Spent mushroom waste | Direct Red 5B | 18.00                | This study                      |
|                 | Direct Black 22 | 15.46               | This study                      |
|                 | Direct Blue 71  | 20.19               | This study                      |
|                 | Reactive Black 5 | 14.62               | This study                      |

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Fig. 6 Plot of ln$K_d$ versus $1/T$ for the thermodynamic evaluation of the adsorption of DR5B, DB22, DB71, and RB5 onto spent mushroom waste
the adsorbent surface shared the charge with a coordinate bond (AlOthman et al. 2014; Munagapati et al. 2018).

As shown in Table 3, negative values of $\Delta G^\circ$ are a result of the adsorption of dyes onto SMW imply physisorption (Alhujaily et al. 2018; Srivastava et al. 2015). Positive values of enthalpy $\Delta H^\circ$ demonstrate the adsorption was endothermic, whereas positive values of $\Delta S^\circ$ suggest that randomness at the solid/liquid interface decreased during the adsorption.

### Adsorption mechanisms

The SMW was characterized in our previous work (Alhujaily et al. 2018). To defend the adsorption mechanisms, several techniques were applied to characterize the SMW surface after adsorption. The adsorption capacity of anionic dyes onto SMW could be described by physical and chemical adsorption processes. The electrostatic interactions were influenced by pH on the anionic adsorption. However, according to kinetics and isotherm, the adsorption of anionic dyes was dominated by chemical adsorption, while thermodynamic analysis suggests physisorption.

Figure 7a shows an SEM image of irregular and porous morphology of the SMW surface. Porous surface is beneficial to the adsorption process. As shown in Fig. 7b, the porous surface was thickened and covered in dyes after the adsorption, which contributed to the physical adsorption.

The FTIR spectra of pristine and DR5B-loaded SMW were compared to determine the potential change of the SMW structure after the adsorption. The spectrum of DR5B-loaded SMW shows similar characteristics to the one of the pristine SMW, except for some peaks whose position and intensity have changed. As shown in Fig. 8, adsorption band at 3426 cm$^{-1}$ was shifted to 3349 cm$^{-1}$ for DR5B-loaded SMW due to the inter- and intramolecular hydrogen bonding of polymeric compounds such as alcohols, phenols, and carboxylic acids in the lignin and cellulose, which refer to the hydroxyl group present on the SMW surface that contribute to the adsorption process (Nasuha and Hameed 2011). The broadband at 1045–1004 cm$^{-1}$ is contributed to the present of $\text{S=O}$ band in the sample (Wong et al. 2019). This establishes the interaction between negatively charged sulfonate $\text{SO}_3^-$ on dyes and positive charge on surface adsorbent. The transmittance percentage becomes higher after the dye adsorption, which indicates the interaction with functional

| Temperature (°C) | Thermodynamic parameters                        |
|------------------|--------------------------------------------------|
|                  | $\Delta G^\circ$ (kJ/mol)  $\Delta H^\circ$ (kJ/mol)  $\Delta S^\circ$ (J/mol K) |
| **DR5B**         |                                                  |
| 20               | −0.787                                          | 0.997                                      | 1.633                                        |
| 30               | −1.077                                          |                                              |                                              |
| 40               | −1.451                                          |                                              |                                              |
| 50               | −1.826                                          |                                              |                                              |
| **DB22**         |                                                  |
| 20               | −0.697                                          | 0.591                                      | 1.650                                        |
| 30               | −0.886                                          |                                              |                                              |
| 40               | −1.133                                          |                                              |                                              |
| 50               | −1.334                                          |                                              |                                              |
| **DB71**         |                                                  |
| 20               | −3.325                                          | 3.79                                       | 7.025                                        |
| 30               | −4.553                                          |                                              |                                              |
| 40               | −5.907                                          |                                              |                                              |
| 50               | −7.475                                          |                                              |                                              |
| **RB5**          |                                                  |
| 20               | −0.153                                          | 0.619                                      | 0.213                                        |
| 30               | −0.278                                          |                                              |                                              |
| 40               | −0.526                                          |                                              |                                              |
| 50               | −0.773                                          |                                              |                                              |

![Fig. 7](image-url) **(A)** Scanning electron micrographs of pristine and DR5B-loaded spent mushroom waste

**Table 3** Thermodynamic analysis for the adsorption of DR5B, DB22, DB71, and RB5 onto spent mushroom waste at different temperatures.
groups on SMW. Therefore, the adsorption mechanisms of dyes on the SMW suggest electrostatic interactions or van der Waals forces (Munagapati et al. 2018; Wakkel et al. 2019).

**Conclusion**

This study demonstrates that SMW can be potentially used as an adsorbent for the elimination of DR5B, DB22, DB71, and RB5 from aqueous solutions. Various parameters affecting adsorption, including pH of the solution, adsorbent dosage, contact time, initial concentration, and temperature were examined to evaluate the adsorption of dyes onto SMW. The results indicate that the adsorption depended on the solution pH, reaching the maximum value at pH 2. The study of the reaction kinetics found that the pseudo-second-order model fitted the experimental data better than the pseudo-first-order and Elovich models. The isotherm study demonstrated that the Langmuir isotherm model described the adsorption better than other models. The monolayer maximum adsorption capacities were found to be 18 mg g⁻¹ for DR5B, 15.46 mg g⁻¹ for DB22, 20.19 mg g⁻¹ for DB71, and 14.62 mg g⁻¹ for RB5. The thermodynamic analysis demonstrated that the adsorption of dyes was spontaneous and endothermic. These results suggest that SMW has good potential to be used as an adsorbent for the dye-containing wastewater, which could help avoid the disposal of SMW and reduce its environmental burden.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare no competing interests.

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**Fig. 8** Fourier transform infrared spectra of pristine and DR5B-loaded spent mushroom waste
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