Activated carbons from coffee husk: Preparation, characterization, and reactive red 195 adsorption

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Abstract
Activated carbons are prepared from coffee husks by chemical activation with ZnCl₂ and are characterized by employing Brunauer, Emmett and Teller, scanning electron microscopy, Fourier-transform infrared spectroscopy, and Boehm titrations. The effects of ZnCl₂/coffee husks, activation temperature, and activation time are studied, and the results show that the sample ACZ3-600-2 has a high surface area of 1383 m² g⁻¹, a high pore volume of 1.648 cm³ g⁻¹, and numerous surface functional groups. The adsorption of reactive red 195 onto the prepared coffee husk activated carbon can be well-described by the pseudo-second-order kinetic model and is found to be controlled by film diffusion followed by intra-particle diffusion. The adsorption isotherm data obtained at 10–40 °C are analyzed and found to follow the Sips model at lower temperatures (10 and 20 °C) and the Redlich–Peterson model at higher temperatures (30 and 40 °C). The obtained thermodynamic parameters (ΔG° < 0, ΔH° = 33.487 kJ mol⁻¹, and ΔS° = 202.30 J K⁻¹ mol⁻¹) suggest that the adsorption of reactive red 195 onto the prepared activated carbon is spontaneous, endothermic, and demonstrates an increasing of randomness at the adsorbate–adsorbent interface. The investigated results show that coffee husk activated carbon is an efficient adsorbent for the removal of reactive red 195 from aqueous solutions.

Keywords
activated carbon, adsorption, coffee husk, mesopore, reactive red 195

Introduction
The textile industry discharges a large amount of dye wastewater, which is difficult to biodegrade and poses severe environmental and health hazards to the communities and the aquatic ecosystem. Among the methods to remove the contaminants from effluents, adsorption has many advantages over others due to its easy operation, low installation cost, large-scale application, and complete removal of impurities from dilute solutions. Adsorbents can be silica gel, alumina, carbon, zeolites, polymers and resins, clay, and so on, in which activated carbon (AC) is a stand-out material owing to its large surface area, high pore volume, and high amount of surface functional groups. Recently, the preparation of AC with the desired chemical and physical properties from agricultural waste has gained significant interest and can be applied as adsorbents in many purification processes such as wastewater treatment, gas cleaning, and metal removal. The properties of AC not only depend on the source precursors but also depend on the activation methods. Generally, chemical activation is more applicable compared to physical activation due to the lower temperature of the process, the higher production yields, and the easier control of AC pore size distribution. In the chemical activation process, the precursor is impregnated with the chemical activating agent, and then heated at a temperature from 400 to 800 °C for a defined time. The activating agents help to develop the porosity of AC through dehydration or degradation processes, which creates pores, cracks, and crevices. According to the literature, the pore size is mostly depended on the types of activation agents. As a general rule, AC activated by (1) alkali compounds, especially KOH, has a majority of micropores, (2) H₃PO₄ includes both micropores and mesopores, and (3) ZnCl₂ possesses mostly mesopores. Note that the appropriate pore size of the adsorbent ensures the effectiveness and selectivity for the specific contaminants that need removal. Large molecules such as dyes should be treated by mesopore-AC. ZnCl₂ activation not
only produces mesopore-AC as demanded but can also lower the activation temperature significantly during the activation process, which is economically beneficial for the activation process.

The aim of this study was to optimize the production of AC using ZnCl₂ activation in a one-step process in order to produce highly mesoporous AC with a pore size suitable for the adsorption of reactive red (RR) 195, a commonly used acidic (anionic) dye. The effects of the ZnCl₂/coffee husk (CFH) ratio, activation temperature, and activation time on the physical properties and the adsorption abilities toward RR 195 of the CFH-AC have been investigated.

Results and discussion

**Physicochemical characterization of AC**

The elemental analysis results of the starting CFH and the obtained ACs are shown in Table 1. It can be seen that besides the two main elements, C and O (more than 45%), CFH also contains about 3.5% of K and trace contents (less than 0.6%) of some other metal elements (Mg, Al, and Ca) and non-metal elements (Si, P, S, and Cl). Heat treatment followed by washing process removed most of the metal and non-metal elements and had a strong effect on the carbon contents of the resulting samples. The carbon content of the sample ACZ0-600-2 (no ZnCl₂) was as high as 86.34%, an increase in more than 50% compared to the precursor. The presence of ZnCl₂ (regardless of the ZnCl₂ ratio) further enhances the carbon content to more than 88%. There was no trace of other metals, especially Zn, observed in the energy-dispersive X-ray (EDX) spectrum, suggesting the effectiveness of the washing process and providing proof of the low level of impurities (ash).

The N₂ adsorption–desorption isotherms conducted at 77 K of the ACs prepared from ZnCl₂ activation at different impregnation ratios, activation temperatures, and activation times are shown in Figure 1. It appears that the presence of ZnCl₂ in the activation process can enhance significantly the surface areas of the obtained ACs, since nitrogen uptake is very high compared to that of the ACZ0-600-2 sample. According to the IUPAC classification, the isotherm of ACZ1-600-2 is defined as type I, which is associated with micropore structures. The others are categorized as a mixed type of I and IV with a hysteresis loop in the \( p/p_0 \) range of 0.5–1.0, indicating the simultaneous presence of micropores and mesopores. The specific surface areas and pore textures determined for the obtained ACs at different impregnation ratios, activation temperatures, and activation times are shown in Table 2. As the ZnCl₂/CFH ratio increases from 1:1 to 3:1, the \( S_{\text{BET}} \) and \( V_{\text{tot}} \) (total pore volume, equal to the sum of \( V_{\text{mic}} \) and \( V_{\text{BJH}} \)) increase from 1049 m² g⁻¹ and 0.5551 cm³ g⁻¹ to 1383 m² g⁻¹ and 1.6482 cm³ g⁻¹, respectively. These changes mostly contributed to the development of mesopores, with the growth of mesopores observed from 25.22% to 87.86% along with the enlargement of \( D_{\text{BJH}} \) from 3.85 to 6.28 nm. At a low ZnCl₂/CFH ratio, ZnCl₂ has a milder effect with respect to the release of volatiles, but at a high ZnCl₂/CFH proportion, the higher ZnCl₂ content provides a more violent response that leads to the widening of pores and subsequently converts the micropores into

| Sample  | Elemental weight % | C    | O    | Mg   | Al   | Si   | P    | S    | Cl   | K    | Ca   |
|---------|--------------------|------|------|------|------|------|------|------|------|------|------|
| CFH     | 49.38              | 45.30| 1.34 | 10.65| 10.96| 10.74| 10.45|      |      |      |      |
| ACZ0-600-2 | 86.34            | 88.34| 88.56| 88.24| 88.50| 88.64|      |      |      |      |      |
| ACZ1-600-2 | 88.56            | 88.56| 88.24| 88.50| 88.64|      |      |      |      |      |      |
| ACZ2-600-2 | 88.56            | 88.56| 88.24| 88.50| 88.64|      |      |      |      |      |      |
| ACZ3-600-2 | 88.56            | 88.56| 88.24| 88.50| 88.64|      |      |      |      |      |      |
| ACZ4-600-2 | 88.56            | 88.56| 88.24| 88.50| 88.64|      |      |      |      |      |      |
When the ZnCl₂/CFH ratio was further increased to 4:1, the \( S_{\text{BET}} \) decreased to 1306 m\(^2\) g\(^{-1}\), while the \( V_{\text{tot}} \) increased to 1.9189 cm\(^3\) g\(^{-1}\). Since carbon in the precursor is a finite amount, the loss of carbon during the activation process at high ZnCl₂ content, on the contrary, will restrict the increase in \( S_{\text{BET}} \).

It can be seen from Table 2 that as the temperature increases from 500 to 600 °C, the \( S_{\text{BET}} \) and \( V_{\text{tot}} \) values increase from 918 to 1383 m\(^2\) g\(^{-1}\) and from 0.8379 to 1.6482 cm\(^3\) g\(^{-1}\), respectively. This increase is due to the evaporation of substances, which directly results from the decomposition of the CFH at elevated temperatures. However, at the activation temperature of 650 °C, the \( S_{\text{BET}} \) value decreases to 1101 m\(^2\) g\(^{-1}\), and \( V_{\text{tot}} \) drops to 1.3404 cm\(^3\) g\(^{-1}\). This is possibly due to the sintering effect, which results in the shrinkage of pores, and consequently reduces the specific surface area and pore volume.

A high temperature also promotes the evaporation of zinc chloride\(^{19}\) and leads to a decrease in the performance of ZnCl₂ at activation temperatures greater than 600 °C.

The effect of activation time is not as pronounced as the other two conditions, even though they follow the same trend. With an increase in the activation time from 1.0 to 2.0 h, \( S_{\text{BET}} \) and \( V_{\text{tot}} \) advance to a certain degree and then decrease when the activation time is further increased to 2.5 h. The reduction in \( S_{\text{BET}} \) and \( V_{\text{tot}} \) is attributable to the seal-off of some portion of pores after a prolonged time.\(^{20}\) The highest specific surface area obtained is found to be 1383 m\(^2\) g\(^{-1}\), which was achieved at a ZnCl₂/CFH ratio of 3:1, an activation temperature of 600 °C, and an activation time of 2.0 h.

The mesopore size distribution of the obtained AC is calculated using the Barrett–Joyner–Halenda (BJH) method\(^{21}\) and is elucidated in Figure 2. Clearly, mesopores are mostly accumulated in the range of 2–25 nm, with a majority at around 4 nm. As seen in Figure 2(a), the mesopore volume increases with a rise in the ZnCl₂/CFH ratio. However, the amount of mesopores with pore sizes from 2 to 10 nm decreases, while the larger pore sizes constantly increase when the ZnCl₂/CFH ratio is as high as 4:1. At this high ZnCl₂/CFH ratio, the vaporization and decomposition of ZnCl₂ happen intensely and result in the enlargement of pores, which in turn lower the amount of pores with pore size less than 10 nm and increase the amount of pores with pore size larger than 10 nm.

Figure 3 shows the morphologies of the ACs prepared at different ZnCl₂/CFH ratios. The AC samples comprise spherical-shaped particles that stack irregularly to form cracks, crevices, and voids. Due to the sufficient amount of activation agent, the ACZ3-600-2 and ACZ4-600-2 samples show a small particle size compared to those of ACZ1-600-2 and ACZ2-600-2.

The Fourier-transform infrared (FTIR) spectra of the ACs are shown in Figure 4. It can be seen that all the FTIR spectra are identical and that most of the absorbance bands are positioned at the same wavenumbers. The band at 3450 cm\(^{-1}\) indicates the presence of the O–H stretching of hydroxy groups, possibly due to the adsorbed water.\(^{22}\) The peak at 1700 cm\(^{-1}\) is ascribed to a C=O stretching of carbonyl.\(^{23}\) The peak located at 1630 cm\(^{-1}\) is associated with stretching of an unsaturated aromatic C=C\(^{24}\) and C=O stretching of a ketone carbonyl. The peak observed at 1390 cm\(^{-1}\) is ascribed to oxygen functionalities such as C=O stretching, O–H bending, and C–O stretching. Finally, the peak at 1070 cm\(^{-1}\) is assigned to C–O stretching of an alcohol.\(^{25}\)

The surface functional groups of the prepared ACs are quantitatively assessed by applying the Boehm titration method, and the results are summarized in Table 3. As can be seen, the ACs prepared via ZnCl₂ activation present both acidic and basic functional groups. The amount of acidic groups (0.94–1.59 mmol g\(^{-1}\)) is always higher than that of the basic groups (0.47–0.57 mmol g\(^{-1}\)), and the acidic group/basic group ratio is in the range of 1.6–2.8. An increase in the ZnCl₂/CFH ratio from 1:1 to 4:1 and the activation time from 1.0 to 2.5 h lead to enhancement of...
both the acidic and basic functional groups; consequently, the acidic group/basic group ratio at different ZnCl₂/CFH ratios and activation times fluctuates from 2.2 to 2.5. However, by increasing the activation temperature from 500 to 650 °C, the amount of acidic groups diminishes from 1.59 to 0.94 mmol g⁻¹, in which the amount of carboxyl groups decreases from 0.68 to 0.42 mmol g⁻¹, although the basic groups remain nearly unchanged (0.52–0.57 mmol g⁻¹). As a result, the acidic group/basic group ratio reduces from 2.8 to 1.6. This result might be due to the diversity in the decomposition temperatures of different functional groups. Carboxyl groups start to decompose at ~250 °C, lactonic groups at ~350 °C, and phenolic groups at 500 °C, while the basic groups decompose at much higher temperatures (650–980 °C). Therefore, the amount of acidic groups decreases faster than that of basic groups, and the carboxyl groups are the most affected.

The point of zero charge (pHₚzc) method measures the pH at which the total number of positive and negative charges on the surface becomes zero. From Figure 5, it can be seen that the pHₚzc values of the ACs prepared at different activation temperatures are in the range of 5.8–6.4, implying the acidic nature of the as-prepared AC surfaces. The acidity of AC surface decreases in the order ACZ3-500-2 > ACZ3-550-2 > ACZ3-600-2 > ACZ3-650-2, which is in the same order as the acidic groups/basic groups ratios and activation times fluctuates from 2.2 to 2.5. However, by increasing the activation temperature from 500 to 650 °C, the amount of acidic groups diminishes from 1.59 to 0.94 mmol g⁻¹, in which the amount of carboxyl groups decreases from 0.68 to 0.42 mmol g⁻¹, although the basic groups remain nearly unchanged (0.52–0.57 mmol g⁻¹). As a result, the acidic group/basic group ratio reduces from 2.8 to 1.6. This result might be due to the diversity in the decomposition temperatures of different functional groups. Carboxyl groups start to decompose at ~250 °C, lactonic groups at ~350 °C, and phenolic groups at 500 °C, while the basic groups decompose at much higher temperatures (650–980 °C). Therefore, the amount of acidic groups decreases faster than that of basic groups, and the carboxyl groups are the most affected.

Adsporption of RR 195

Effect of activation conditions

The adsorption capacity of the ACs prepared under different activation conditions was investigated under the experimental conditions of an initial RR 195 concentration of 200 mg L⁻¹, a pH of 2.5, an AC dose of 1.0 g L⁻¹, and a temperature of 30 °C, and the results are shown in Figure 6. It is apparent that the sample activated without the activation agent has a very small qₑ value (5.57 mg g⁻¹) compared to others, which is due to its low specific surface area and pore volume.

It also can be seen from Figure 6 that the impregnation ratio has the most noticeable effect and that the activation time has the least influence on the adsorption ability of the prepared ACs. The qₑ value increases significantly from sample ACZ1-600-2 (139.45 mg g⁻¹) to sample ACZ3-600-2 (188.12 mg g⁻¹) when the impregnation ratios increase from 1:1 to 3:1, while fluctuations occur between 177.12 and 188.12 mg g⁻¹ when the activation times increase from 1 to 2.5 h. For the effect of the activation temperature, the adsorption capacity increases from 160.66 to 188.12 mg g⁻¹ and then decreases to 173.87 mg g⁻¹ as the activation temperature increases from 500 to 650 °C.

The change in the RR 195 adsorption capacity of the AC samples is similar to the change in specific surface area and pore volume, especially those of mesopores (see Table 2), and thus can be explained according to these variables. The ACs that have a higher specific surface area and mesopore volume will have a greater adsorption capacity.
percentage from 55.18% to 99.05%, which is due to the increase in surface area and adsorption sites. However, the equilibrium adsorption capacity decreases from 220.70 to 113.20 mg g\(^{-1}\) when the AC amount increases from 0.5 to 1.75 g L\(^{-1}\). The drop in the RR 195 adsorption capacity with the adsorbent dosage might be associated with the unsaturated adsorption degree of the AC. At an activated dosage higher than 1.0 g L\(^{-1}\), the increase in adsorbent dose did not change the RR 195 removal appreciably but reduced the adsorption capacity significantly. Therefore, for further experiments, the AC dose is fixed at 1.0 g L\(^{-1}\).

The effect of the pH on the removal efficiency of RR 195 and the adsorption capacity of CFH-AC was conducted in the pH range of 1.5–9.0 and is shown in Figure 8. It can be seen from Figure 8 that both the removal percentage and the adsorption capacity decrease as the pH increases. At a pH greater than 3.0, both the percentage removal and the adsorption capacity reduce quickly. The reason is associated with the value of pH\(_{ZPC}\) of the AC. The pH\(_{ZPC}\) value of ACZ3-600-2 is around 6.2, so at a pH less than 6, the AC surface is positively charged, which promotes the attraction force between the AC and RR 195 (an anionic dye, negatively charged). As the pH increases to over 6.2, the AC surface becomes negatively charged, leading to the enhancement of the repulsive force between the AC and RR 195, and thus lowering the RR 195 adsorption capacity of the AC sample.

Based on the above investigation and considering the RR 195 removal as well as the adsorption capacity, a pH value of 2.5 was selected for further study.

**Adsorption kinetic.** Figure 9 shows the kinetics of the adsorption of RR 195 onto the ACZ3-600-2 sample with different initial concentrations (150–300 mg L\(^{-1}\)) and at four temperatures (10–40 °C). The shapes of all the kinetic curves are similar and consist of a fast adsorption range (0–60 min), followed by a slow adsorption range, and then reaching equilibrium. The fast adsorption process during the initial stage is attributed to the abundant active sites for adsorption, and the gradual rate of adsorption might be due to the occurrence of pore diffusion resistance. The time required to reach equilibrium for the adsorption of RR 195 onto CFH-AC at a concentration of 150–300 mg L\(^{-1}\) and a temperature of 10–40 °C is estimated to be 240 min.

The adsorption kinetics of the adsorption of RR 195 onto the ACZ3-600-2 sample was estimated using the three common kinetic models in their linear forms as follows:

\[
\text{Pseudo-first-order (PFO): } \ln(q_e - q_t) = \ln q_e - k_1 t
\]

\[
\text{Pseudo-second-order (PSO): } \frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t
\]

\[
\text{Elovich: } q_t = (1/\beta) \ln (\alpha \beta) + (1/\beta) \ln (t)
\]

where \(q_t\) and \(q_e\) (mg g\(^{-1}\)) are the amounts of RR 195 adsorbed at time \(t\) (min) and at equilibrium, respectively, \(k_1\) (min\(^{-1}\)) and \(k_2\) (g mg\(^{-1}\) min\(^{-1}\)) are the rate constants of pseudo-first-order (PFO) and pseudo-second-order (PSO) adsorption, respectively, \(\alpha\) is the initial adsorption rate (mg g\(^{-1}\) min\(^{-1}\)), and \(\beta\) is the desorption constant (g mg\(^{-1}\)).

The parameters of these equations were obtained using linear regression. The validity of these models was evaluated by the coefficient of determination (\(R^2\)) and the average relative errors (AREs). The model with the highest \(R^2\) value and the lowest ARE value is considered to be the most applicable model, which presents a good correlation between experimental data and the kinetic equation as well as between the empirical and predicted data. The values of ARE were obtained using equation (4):

\[
\text{ARE} = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{q_{t,\text{pred}} - q_{t,\text{mes}}}{q_{t,\text{mes}}} \right|
\]
Figure 3. SEM images of the as-prepared activated carbons at different impregnation ratios.

Figure 4. FTIR spectra of AC samples prepared at different (a) impregnation ratios (activation temperature: 600 °C and activation time: 2 h), (b) activation temperatures (ZnCl₂/CFH ratio: 3:1 and activation time: 2 h), and (c) activation times (ZnCl₂/CFH ratio: 3:1 and activation temperature: 600 °C).
where $q_{\text{t,exp}}$ and $q_{\text{t,pred}}$ are the experimental and predicted amount of RR 195 adsorbed at time $t$, respectively; and $N$ is the number of experimental data.

Figure 10 demonstrates the fitting lines of PFO, PSO, and the Elovich models for adsorption of RR 195 onto ACZ3-600-2 at dye concentrations in the range of 150–300 mg L$^{-1}$, at 30 °C, and a pH of 2.5. It can be seen that the PSO kinetic model has a much better correlation fit for the RR 195 adsorption data than the PFO and Elovich models for all the conditions investigated. The parameters of the models at different initial RR 195 concentrations and adsorption temperatures are calculated and are summarized in Table 4. It was observed that the $R^2$ values were closest to 1 when applying the PSO model. Besides, ARE value of the PSO model is relatively small (0.43%–0.93%), compared to that of the PFO model (60.70%–70.67%) and the Elovich model (3.30%–4.17%). Furthermore, the $q_e$ value calculated using the PSO model is from 146.63 to 255.1 mg g$^{-1}$, which is in the same range as the

### Table 3. Surface functional groups of the AC samples.

| Label | Carboxyl (mmol g$^{-1}$) | Lactone (mmol g$^{-1}$) | Phenol (mmol g$^{-1}$) | Acidic groups (mmol g$^{-1}$) | Basic groups (mmol g$^{-1}$) | Acidic groups/basic groups |
|-------|-------------------------|--------------------------|------------------------|-------------------------------|----------------------------|----------------------------|
| ZnCl$_2$/CFH ratio (activation temperature: 600 °C and activation time: 2 h) |
| 1:1   | ACZ1-600-2 | 0.39 | 0.28 | 0.37 | 1.04 | 0.48 | 2.2 |
| 2:1   | ACZ2-600-2 | 0.48 | 0.32 | 0.36 | 1.16 | 0.51 | 2.3 |
| 3:1   | ACZ3-600-2 | 0.53 | 0.35 | 0.32 | 1.20 | 0.54 | 2.2 |
| 4:1   | ACZ4-600-2 | 0.67 | 0.36 | 0.38 | 1.41 | 0.56 | 2.5 |
| Activation temperature (°C) (ZnCl$_2$/CFH ratio: 3:1 and activation time: 2 h) |
| 500   | ACZ3-500-2 | 0.68 | 0.45 | 0.46 | 1.59 | 0.56 | 2.8 |
| 550   | ACZ3-550-2 | 0.57 | 0.41 | 0.38 | 1.36 | 0.52 | 2.6 |
| 600   | ACZ3-600-2 | 0.53 | 0.35 | 0.32 | 1.20 | 0.54 | 2.2 |
| 650   | ACZ3-650-2 | 0.42 | 0.29 | 0.23 | 0.94 | 0.57 | 1.6 |
| Activation time (h) (ZnCl$_2$/CFH ratio: 3:1 and activation temperature: 600 °C) |
| 1     | ACZ3-600-1 | 0.46 | 0.37 | 0.33 | 1.16 | 0.49 | 2.4 |
| 1.5   | ACZ3-600-1.5 | 0.49 | 0.33 | 0.37 | 1.19 | 0.47 | 2.5 |
| 2     | ACZ3-600-2 | 0.53 | 0.35 | 0.32 | 1.20 | 0.54 | 2.2 |
| 2.5   | ACZ3-600-2.5 | 0.52 | 0.35 | 0.32 | 1.19 | 0.55 | 2.2 |

AC: activated carbon; CFH: coffee husk.
experimental $q_e$. Therefore, it can be concluded that the PSO model is well-fitted for the adsorption of RR 195 onto CFH-AC.

It can also be seen from Table 4 that the rate constant of PSO adsorption decreases with an increase in the initial RR 195 concentration and increases with a rise in the adsorption temperature. However, the initial adsorption rate, $h_o$ (mg g$^{-1}$ min$^{-1}$), which is calculated using equation (5) is unaffected by the initial RR 195 concentration, while it increases immensely with an increase in the temperature. The constant $h_o$ at different adsorbate concentrations is due to the sufficient number of mesopores in the ACs, which facilitate the transport of dye molecules at the surface and inside the pores. Nevertheless, the heat diffusion rate of the dye molecule at high temperatures resulted in an increase in $h_o$ at elevated temperatures

$$h_o = k_2 q_e^2$$

(5)

The activation energy ($E_a$) of the adsorption of RR 195 onto CFH-AC was calculated using the Arrhenius equation

$$\ln k_2 = \ln A - \frac{E_a}{RT}$$

(6)

where $k_2$ is the PSO rate constant (g g$^{-1}$ s$^{-1}$), $E_a$ is the activation energy (kJ mol$^{-1}$), $A$ is the Arrhenius factor, $R$ is the gas constant (8.314 J mol$^{-1}$ K$^{-1}$), and $T$ is the absolute temperature (K).

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**Figure 8.** Effect of the different pH on the adsorption capacity and the removal of RR 195 ($C_0=200$ mg L$^{-1}$ and AC dose: 1.0 g L$^{-1}$).

**Figure 9.** Adsorption kinetics of RR 195 using the ACZ3-600-2 sample at different (a) initial concentrations and (b) temperatures (pH=2.5; the solid curves were calculated by the PSO equation).

**Figure 10.** (a) The PFO and PSO and (b) the Elovich kinetic models for RR 195 adsorption at 30 °C to the ACZ3-600-2 sample (the solid, dashed, and dotted lines are calculated from the PSO, PFO, and Elovich equations, respectively).
From the slope of the linear plot of $\ln k_2$ versus reciprocal temperature (Figure 11), the activation energy is found to be 8.558 kJ mol$^{-1}$. The value of $E_a$ infers that the adsorption of RR 195 onto CFH-AC is the physisorption process.

Generally, the adsorption process of a dye involves three sequential processes: (1) film diffusion: the dye is adsorbed on the external part of the AC, (2) particle diffusion: transport and adsorption of dye molecules within the pores of the AC occurs, and (3) physisorption or chemisorption of the dye molecules on the inner surface of the AC. Step (3) is relatively fast, but it is not the rate-determining step.\textsuperscript{29} In order to determine the rate-determining step for the adsorption of RR 195 onto AC, the experimental data were further investigated using the Weber and Morris model, which is shown in equation (7)

$$q_t = k_d t^{1/2} + C$$

where $C$ is the intercept and $k_d$ is the intra-particle diffusion rate constant.

The plots of $q_t$ versus $t^{1/2}$ for the adsorption of RR 195 onto the ACZ3-600-2 sample at different initial concentrations of RR 195 and temperatures are shown in Figure 12. These lines do not pass through the origin and contain two straight lines, implying that the intra-particle is not the sole rate-limiting step.\textsuperscript{30} In order to determine the rate-determining step for the adsorption of RR 195 onto AC, the experimental data were further investigated using the Weber and Morris model, which is shown in equation (7)

$$q_t = k_d t^{1/2} + C$$

where $C$ is the intercept and $k_d$ is the intra-particle diffusion rate constant.

The calculated adsorption rate, the $C$ constant, and the coefficient of determination are summarized in Table 5. It can be seen that the $R^2$ values are relatively high, implying the good fit between the model and the experimental data. The rate of diffusion in the initial stage is much larger than that of the second stage. The adsorption rate during both stages increases with the increase in initial RR 195 concentrations and temperatures. This is due to the promotion effect on the diffusion rate at the higher concentration gradients and temperatures.

### Adsorption isotherms

The RR 195 uptakes of the ACZ3-600-2 sample at four different adsorption temperatures (10, 20, 30, and 40 °C) are displayed in Figure 13. As can be seen, the adsorbed amounts of RR 195 increase with RR 195 concentration, rather sharply in the region of concentration less than 40 mg L$^{-1}$ and more smoothly at higher concentration. Besides, the RR 195 adsorption increases with temperature, which shows the endothermic characteristic of the process. At all temperatures studied, the isotherms display no plateau, indicating unsaturated adsorption under the investigated conditions.

The distribution of the adsorbate and the interaction between the adsorbate and AC sample at equilibrium are investigated using two-parameter models, namely, the Langmuir, Freundlich, and Elovich isotherms, and

### Table 5. The parameters of the adsorption of RR 195 onto the ACZ3-600-2 sample calculated from kinetic models.

| $C_o$ (mg L$^{-1}$) | 150  | 200  | 250  | 300  | 200  | 200  | 200  | 200  | 200  |
|--------------------|------|------|------|------|------|------|------|------|------|
| $T$ (°C)           | 30   | 30   | 30   | 30   | 10   | 20   | 40   |      |      |
| Experimental $q_e$ (mg g$^{-1}$) | 146.64 | 188.12 | 225.43 | 254.09 | 179.26 | 184.63 | 193.87 |      |      |
| Pseudo-first-order model | $q_e$ (mg g$^{-1}$) | 71.24 | 93.98 | 123.25 | 151.37 | 102.24 | 98.60 | 88.03 |      |
|                    | $k_1 \times 10^3$ (min$^{-1}$) | 9.24  | 9.22  | 8.61  | 8.53  | 8.55  | 9.11  | 10.00 |      |
|                    | $R^2$ | 0.9447 | 0.9418 | 0.9421 | 0.9555 | 0.95017 | 0.9523 | 0.9446 |      |
|                    | ARE (%) | 69.05 | 67.95 | 64.87 | 60.70 | 62.93 | 66.09 | 70.67 |      |
| Pseudo-second-order model | $q_e$ (mg g$^{-1}$) | 146.63 | 188.68 | 225.23 | 255.10 | 179.53 | 185.53 | 195.31 |      |
|                    | $k_2 \times 10^4$ (g mg$^{-1}$ min$^{-1}$) | 3.82 | 2.80 | 1.97 | 1.47 | 2.27 | 2.53 | 3.24 |      |
|                    | $h_o$ (mg g$^{-1}$ min$^{-1}$) | 8.2 | 10.0 | 10.0 | 9.6 | 7.3 | 8.7 | 12.4 |      |
|                    | $R^2$ | 0.9999 | 0.9999 | 0.9998 | 0.9995 | 0.9999 | 0.9998 | 0.9999 |      |
|                    | ARE (%) | 0.93 | 0.43 | 0.55 | 0.84 | 0.58 | 0.75 | 0.51 |      |
| Elovich model      | $\alpha$ (mg g$^{-1}$ min$^{-1}$) | 28.94 | 31.81 | 27.31 | 24.10 | 19.20 | 25.53 | 49.65 |      |
|                    | $\beta$ (g mg$^{-1}$) | 0.039 | 0.030 | 0.023 | 0.020 | 0.029 | 0.029 | 0.031 |      |
|                    | $R^2$ | 0.9999 | 0.9999 | 0.9998 | 0.9995 | 0.9999 | 0.9998 | 0.9999 |      |
|                    | ARE (%) | 3.86 | 4.17 | 4.08 | 3.30 | 3.39 | 3.76 | 4.00 |      |

**Figure 11.** Plot of $\ln k_2$ versus $1/T$.  

**Figure 12.** Plots of $q_t$ versus $t^{1/2}$, showing the two stages of diffusion.
three-parameter models including the Radke–Prausnitz, Redlich–Peterson, Sips, and Tóth isotherms. The models applied to the adsorption data are introduced in Table 6. The parameters of the seven isotherms equations for the RR 195 adsorption on ACZ3-600-2 were evaluated using non-linear regression by minimizing the root mean square error (RMSE). The applicability of these equations is verified through the coefficient of determination ($R^2$) and ARE.

In this case, RMSE, $R^2$, and ARE are calculated according to equations (8), (9), and (10), respectively

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (q_{e,\text{pre}} - q_{e,\text{mes}})^2}$$  \hspace{1cm} (8)

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (q_{e,\text{mes}} - q_{e,\text{pre}})^2}{\sum_{i=1}^{N} (q_{e,\text{mes}} - q_{e,\text{mean}})^2}$$  \hspace{1cm} (9)

$$\text{ARE} = \frac{100}{N} \sum_{i=1}^{N} \left( \frac{q_{e,\text{pre}} - q_{e,\text{mes}}}{q_{e,\text{mes}}} \right)$$  \hspace{1cm} (10)

where $q_{e,\text{mes}}$, $q_{e,\text{pre}}$, and $q_{e,\text{mean}}$ are the experimental, predicted, and average adsorption capacities, respectively; and $N$ is the number of experimental data.

The obtained results using the two-parameter equations to describe the adsorption equilibrium are shown in Figure 13, and the corresponding parameters are summarized in Table 7. Even though the $R^2$ values observed for the Elovich model are close to 1, the associated $q_m$ is in the range of 52.92–67.31 mg g$^{-1}$, which is far from the experimental value. Therefore, the Elovich model is not applicable to fit the experimental data.

Other two-parameter models also show a good correlation between the experimental data and the model with $R^2$ in the range of 0.9303–0.9998. However, ARE values are rather high for the Freundlich isotherm at temperatures of...
10 and 20 °C, and the Langmuir isotherm at temperatures of 30 and 40 °C. Therefore, for describing the experimental data using two-parameter isotherms, the Langmuir model is suitable for use at lower temperatures (10 and 20 °C) and the Freundlich model is relevant at higher temperatures (30 and 40 °C). The small $K_L$ value and $1/n < 1$ suggest that the adsorption of RR 195 onto CFH-AC is favorable for all the temperatures investigated.

The $q_m$ value calculated by the Langmuir equation increases with the adsorption temperature and is in the range of 257.07–297.27 mg g$^{-1}$, suggesting that the CFH-AC has a good adsorption capacity for RR 195 removal and is comparable with TiO$_2$ nanoparticles (87 mg g$^{-1}$),28 poly-pyrrole composite (204.08 mg g$^{-1}$),29 dried soybean leaves modified with acetic acid (12 mg g$^{-1}$),30 chitosan particles (82.1 mg g$^{-1}$),29 and AC (1.2 mg g$^{-1}$).30

For all the three-parameter models investigated, including Radke–Prausnitz, Redlich–Peterson, Sips, and Tóth, the isotherms are illustrated in Figure 14, and the corresponding parameters are summarized in Table 8. All the fitting curves go through most of the experimental points, and the coefficient of determination values, $R^2$, are higher than 0.9853 suggesting the good correlation between the experimental data and the model applied. However, the $q_{m}$ values calculated from the Radke–Prausnitz isotherm do not follow the same trend as the experimental values, indicating the unsuitability when using this model for representing the adsorption of RR 195 onto CFH-AC at equilibrium. The other four equations have ARE values that lie between 1.02% and 2.29%, indicating that they all can describe the experimental data better than the two-parameter equation. It is observed that the AREs are smallest when using the Sips model at 10 and 20 °C (ARE is 1.14% and 1.09%) and applying the Redlich–Peterson model at 30 and 40 °C (ARE is 1.70% and 0.87%).

Therefore, in general, the three-parameter models are more suitable to describe the adsorption equilibrium of RR 195 onto CFH-AC than the two-parameter models. In all the

### Table 6. The isotherm models and the parameters involved.

| Isotherm          | Expression | Parameters | References          |
|-------------------|------------|------------|---------------------|
| Langmuir          | $q = q_m K_L C_e / (1 + K_L C_e)$ | $q_m$: maximum monolayer coverage capacity, $K_L$: Langmuir isotherm constant | Dabrowski$^{32}$ and Hamdaoui and Naffrechoux$^{33}$ |
| Freundlich        | $q = K_F C_e^n$ | $K_F$: Freundlich isotherm constant, $n$: parameter related with multiple layer coverage | Hamdaoui and Naffrechoux$^{33}$ and Ayawei et al.$^{34}$ |
| Elovich           | $q_e = \frac{K_e}{q_m} \exp \left( -\frac{q_e}{q_m} \right)$ | $q_e$: maximum monolayer coverage capacity, $K_e$: Elovich equilibrium constant | Dabrowski$^{32}$ |
| Radke–Prausnitz   | $q = q_{mRP} K_{RP} C_e^{1/mRP}$ | $q_{mRP}$: Radke–Prausnitz maximum adsorption capacity, $K_{RP}$: Radke–Prausnitz equilibrium constants. | Ayawei et al.$^{34}$ |
| Redlich–Peterson  | $q = \frac{AC_e}{1 + BC_e^\beta}$ | $A$ and $B$: Redlich–Peterson isotherm constant, $\beta$: Redlich–Peterson model exponent | Ayawei et al.$^{34}$ and Hamdaoui and Naffrechoux$^{35}$ |
| Sips              | $q = q_m K_S C_e^{m_s}$ | $q_m$: Sips maximum adsorption capacity, $K_S$: Sips equilibrium constant, $m_s$: Sips model exponent. | Hamdaoui and Naffrechoux$^{35}$ |
| Tóth              | $q = \frac{q_m C_e}{(1/K_T + C_e^{m_T})^{1/m_T}}$ | $q_m$: Tóth maximum adsorption capacity, $K_T$: Tóth equilibrium constant, $m_T$: Tóth model exponent | Hamdaoui and Naffrechoux$^{35}$ |

### Table 7. Parameters of the Langmuir, Freundlich, and Elovich isotherms for the adsorption of RR 195 onto ACZ3-600-2 at different temperatures.

| Model          | Parameter | Adsorption temperature |
|----------------|-----------|------------------------|
| Langmuir       | $q_m$ (mg g$^{-1}$) | 10 °C 20 °C 30 °C 40 °C |
|                | $K_L$ (L mg$^{-1}$) | 0.111 0.133 0.165 0.258 |
|                | $R^2$      | 0.9998 0.9991 0.9970 0.9976 |
|                | ARE (%)    | 1.14 1.76 4.99 5.79 |
| Freundlich     | $K_F$ (mg$^{1-n}$ L$^{1/n}$ g$^{-1}$) | 75.044 84.158 112.117 128.884 |
|                | $N$        | 3.735 3.810 4.736 5.050 |
|                | $R^2$      | 0.9302 0.9468 0.9892 0.9820 |
|                | ARE (%)    | 5.07 4.85 1.72 2.28 |
| Elovich        | $q_m$ (mg g$^{-1}$) | 67.31 67.16 55.94 52.92 |
|                | $K_E$ (L mg$^{-1}$) | 1.577 2.326 8.875 19.570 |
|                | $R^2$      | 0.9270 0.9544 0.9818 0.9919 |

RR 195: reactive red 195; ARE: average relative error.
models investigated, the Sips model best describes the adsorption equilibrium at 10 and 20 °C, while the Redlich–Peterson equation best describes the same equilibrium at 30 and 40 °C.

**Thermodynamic studies**

Thermodynamic parameters including the standard Gibbs free energy change ($\Delta G^\circ$), the enthalpy change ($\Delta H^\circ$), and the entropy change ($\Delta S^\circ$) of the adsorption of RR 195 onto CFH-AC are determined using following equations

$$\Delta G^\circ = -RT \ln K_o \quad (11)$$

$$\ln K_o = -\frac{\Delta H^\circ}{R} \times \frac{1}{T} + \frac{\Delta S^\circ}{R} \quad (12)$$

where $R$ is the universal gas constant (8.314 J mol$^{-1}$ K$^{-1}$), $T$ is the temperature (K), and $K_o$ is the equilibrium constant and can be calculated using following equation$^{41}$

$$K_o = \lim_{C_e \to 0} \frac{q_e}{C_e} \quad (13)$$

where $C_e$ (mg mL$^{-1}$) is the equilibrium concentration and $q_e$ (mg g$^{-1}$) is the amount of RR 195 adsorbed at equilibrium calculated according to the Sips (10 and 20 °C) or the Redlich–Peterson (30 and 40 °C) isotherms, with the parameters listed in Table 8.

The intercept of the plot of $\ln(q_e/C_e)$ versus $C_e$ gives the value of $K_o$ (data not shown). The calculated $\Delta G^\circ$, $\Delta H^\circ$, and $\Delta S^\circ$ values are summarized in Table 9. A negative value of $\Delta G^\circ$ and a positive value of $\Delta H^\circ$ reflect the spontaneous and endothermic nature of the adsorption process. The values of both $\Delta G^\circ$ and $\Delta H^\circ$ are slightly larger than the value of physical adsorption ($-20$ to $0$ kJ mol$^{-1}$ for $\Delta G^\circ$ and $2.1$–$20.9$ kJ mol$^{-1}$ for $\Delta H^\circ$)$^{42}$ but not up to the chemisorption range ($-80$ to $-400$ kJ mol$^{-1}$)$^{43}$ suggesting that the adsorption of RR 195 onto ACZ-600-2 is mainly physisorption and promoted by chemisorption. The chemisorption is due to the surface functional groups of AC which can form donor-acceptor complexes with RR 195, thus contributing to RR 195 adsorption. The positive value of $\Delta S^\circ$ demonstrates the increase in randomness at the adsorbate-adsorbent interface, which might be due to the competition adsorption between RR 195 and the solvent molecules as well as the breakage of the hydration shell of RR 195 molecules during the adsorption onto the ACZ-600-2 sample.$^{44}$

**Scale-up design.** The batch adsorption process is usually designed based on the adsorption isotherm.$^{45}$ It is assumed that when RR 195 is mixed with $W$ mass of AC from CFHs,
the RR 195 concentration is decreased from \( C_0 \) to \( C_t \) in a solution volume \( V \) at any specific time wherein the adsorbed RR 195 quantity of each gram of the AC which can form donor–acceptor complexes with RR 195, thus contributing to RR 195 adsorption. The positive value of \( \Delta S^\circ \) demonstrates the increase in randomness at the adsorbate–adsorbent interface, which might be wherein the adsorbed RR 195 quantity of each gram of the AC is altered from \( q_o \) to \( q_t \).

When \( t=0 \), \( q_o = 0 \), and the mass balance is expressed as equation (14)

\[
V(C_o - C_t) = W(q_t - q_o) = Wq_t
\]

At equilibrium, \( C_e = C_t \) and \( q_e = q_t \), equation (14) is modified as equation (15)

\[
W = \frac{V(C_o - C_e)}{q_t} = \frac{V(C_o - C_e)}{q_e}
\]

Using the best supportive Sips and Redlich–Peterson models for the adsorption at 20 and 30 °C, respectively, equation (15) is modified to form equations (16) and (17)

\[
\begin{align*}
W & = \frac{V(C_o - C_e)(1 + K_{sp}C_{sp})}{q_m K_{sp} C_{sp}} \\
W & = \frac{V(C_o - C_e)(1 + BC_{sp})}{AC_e}
\end{align*}
\]

Using equations (16) and (17) with the parameters from Table 8, the required weight of AC from CFH for the removal of RR 195 with a concentration of 150 mg L\(^{-1}\) at 20 and 30 °C for different volumes (2–10 L) of aqueous RR 195 solutions (wastewater or effluent) was evaluated and the results are given in Table 10.

It can be seen from Table 10 that it is easier to remove RR 195 at 30 °C than at 20 °C as the weight of AC was always lower. This is due to the better adsorption ability of ACZ-600-2 at elevated temperature. The required amount of ACs is relatively low, only 0.4980 and 0.4631 g L\(^{-1}\) at 20 and 30 °C, respectively, to remove 75% of the initial RR 195 concentration of 150 mg L. This result suggests the applicability of CFH-AC for the removal of RR 195 from wastewater.

**Conclusion**

In this work, the preparation of AC from CFHs by chemical activation with ZnCl\(_2\) as an activating agent using a one-step process has been investigated. The obtained ACs present a high specific surface area (918–1383 m\(^2\) g\(^{-1}\)) with predominantly mesoporous (25.22%–91.91% mesopore volume). Under the optimized condition of a ZnCl\(_2\)/CFH mass ratio of 3:1, an activation temperature of 600 °C, and an activation time of 2 h, the \( S_{BET}, S_{BH}, V_{BHP} \) and \( V_{tot} \) values are...
Table 10. Weight of activated carbon (g) for the removal of RR 195 (%) at 20 and 30 °C for different volumes of RR 195 solution.

| V (L) | 20 °C | 30 °C |
|-------|-------|-------|
|       | 25%   | 50%   | 75%   | 90%   | 25%   | 50%   | 75%   | 90%   |
| 2     | 0.295 | 0.609 | 0.996 | 1.482 | 0.255 | 0.546 | 0.926 | 1.322 |
| 4     | 0.590 | 1.218 | 1.992 | 2.965 | 0.510 | 1.093 | 1.852 | 2.644 |
| 6     | 0.885 | 1.826 | 2.988 | 4.447 | 0.764 | 1.639 | 2.778 | 3.965 |
| 8     | 1.880 | 4.235 | 3.984 | 5.930 | 1.019 | 2.185 | 3.704 | 5.287 |
| 10    | 1.475 | 3.044 | 4.980 | 7.412 | 1.274 | 2.732 | 4.631 | 6.609 |

RR 195: reactive red 195.

1383 m² g⁻¹, 922 m² g⁻¹, 1.4481 cm³ g⁻¹, and 1.6482 cm³ g⁻¹, respectively. The adsorption of RR 195 from aqueous solution onto AC follows a PSO equation, with an activation energy of 8.558 kJ mol⁻¹, which is controlled by the external and intra-particle diffusion mass transfers. The equilibrium data fit well with the Sips model (at 10 and 20 °C) or the Redlich–Peterson model (at 30 and 40 °C). The adsorption process is mainly physisorption and is promoted by chemisorption with an enthalpy change of 33.487 kJ mol⁻¹. The isotherms were evaluated at 77 K using an automated gas adsorption analyzer, TriStar 3000-Micromeritics, from which the specific surface area (Sₚₛₚₑ), the micropore surface area (Sₘᵢｃ), the micropore volume (Vₘᵢｃ), the mesopore surface area (Sₘₑᵦ), the mesopore volume (Vₘₑᵦ), and the average of mesopore width (Dₘₑᵦ) were estimated. The morphology was examined by a high-resolution field-emission scanning electron microscope, S4800 (Hitachi). The FTIR spectra were recorded using an FTIR spectroscope, Nexus 670 spectrometer (Nicoleit). The surface functional groups of the AC were determined by the Boehm titration method. pHₚₑᵢᵦ was evaluated by the pH drift method, using a CP-501 pH-meter.

**AC characterization**

The chemical compositions of the prepared AC samples were determined using an energy-dispersive X-ray spectroscopy, EDX-LE VIOEL 6610 LV (Jeol). Nitrogen adsorption isotherms were evaluated at 77 K using an automated gas adsorption analyzer, TriStar 3000-Micromeritics, from which the specific surface area (Sₚₛₚₑ), the micropore surface area (Sₘᵢｃ), the micropore volume (Vₘᵢｃ), the mesopore surface area (Sₘₑᵦ), the mesopore volume (Vₘₑᵦ), and the average of mesopore width (Dₘₑᵦ) were estimated. The morphology was examined by a high-resolution field-emission scanning electron microscope, S4800 (Hitachi). The FTIR spectra were recorded using an FTIR spectroscope, Nexus 670 spectrometer (Nicoleit). The surface functional groups of the AC were determined by the Boehm titration method. pHₚₑᵦ was evaluated by the pH drift method, using a CP-501 pH-meter.

**Experimental**

**Materials**

Zinc chloride (CAS: 7646-85-7, purity ≥ 98%) was supplied by Xilong Chemical, China. RR 195 (CAS: 93050-79-4, chemical formula: C₃₁H₁₉O₁₉N₇S₆Na₅Cl) was provided by Shanghai Anoky Group Co., Ltd., China. RR 195 (CAS: 98%) was supplied by Xilong Chemical, China. RR 195 (CAS: 93050-79-4, chemical formula: C₃₁H₁₉O₁₉N₇S₆Na₅Cl) was provided by Shanghai Anoky Group Co., Ltd., China. ACs were prepared from Arabica CFHs (Son La Province, Vietnam) using the one-step process. Before use, the CFH precursor was washed and oven-dried at 120 °C for 12 h, followed by grinding and sieving to a particle size of about 1.0 mm. The required amount of ZnCl₂ was dissolved in about 100 mL of distilled water at 100 °C and then 20 g of the crushed CFH was added. The mixture was continuously stirred at 100 °C for 1 h, then oven-dried at 120 °C for 12 h. Afterward, the resulting samples were activated in a vertical cylindrical furnace with a nitrogen flow rate of 300 mL min⁻¹ at four different temperatures (500–650 °C) for a specific amount of time (1–2.5 h) using a heating rate of 10 °C min⁻¹. After cooling, the product was immersed in a 0.5-M HCl solution for 12 h to leach out the ZnCl₂. The filtered solution was kept for recycling, and the solid component was washed several times with hot water and finally with cold distilled water until constant pH (~6.0). The washed AC samples were subsequently dried at 120 °C for 24 h and stored in a desiccator. The samples were labeled as ACZa-b-c, in which “a” is the ZnCl₂/CFH mass ratio, “b” is the activation temperature (°C), and “c” is the activation time (h).

RR 195 stock solution of 1.0 g L⁻¹ was prepared within 24 h prior to use by dissolving solid RR 195 in double distilled water. The stock solution was then diluted to obtain solutions of various concentrations. The pH of the solution was adjusted with HCl and NaOH (1 M). The concentrations of RR 195 were determined using a UV-Vis spectrophotometer (LIUV-310S) at the maximum wavelength of 541 nm.

**RR 195 adsorption experiments**

In the adsorption experiment, the AC samples were ground and sieved to a particle size range of 0.15 < d < 0.3 mm (mesh nos. 100 and 50) to ensure repetition. Each experiment was performed in triplicate and the results are presented as mean values.

For determining the optimum AC dose and pH, the experiment was carried out in a 250-mL Erlenmeyer flask containing a mixture of 100 mL of RR 195 solution (200 mg L⁻¹) and a fixed amount of AC sample (AC dose: 0.5–1.75 g L⁻¹) at different pH (1.5–9.0) values. The flask was kept in an isothermal shaker (120 rpm⁻¹) at 30 °C for 24 h to reach equilibrium. After filtration, the equilibrium concentrations of RR 195 in the solution were determined using a spectrophotometer. The amount of RR 195 adsorption at equilibrium qₑ (mg g⁻¹) and the percentage removal (%) of RR 195 were calculated using the following equations

$$qₑ = \frac{(C_o - Cₑ)V}{m}$$

$$RR 195 \text{ removal } (%) = \frac{(C_o - Cₑ)100}{C_o}$$

where Cₒ and Cₑ (mg L⁻¹) are the RR 195 concentrations at initial and equilibrium, respectively. V (L) is the volume of the solution, and m (g) is the mass of AC used.
Kinetic experiments were conducted in 300-mL flasks containing 0.25 g of the AC with 250 mL of RR 195 solution of different concentrations (150–300 mg L⁻¹) and at the optimal pH. The flasks were kept in a temperature-controlled water bath (10–40 °C) and the aqueous solution-adsorbent mixtures were stirred at 200 min⁻¹. At a preset time intervals, 5 mL of the mixtures were pipetted out, filtered, and the RR 195 concentrations were measured using a spectrophotometer. The amount of RR 195 adsorbed at time t, \(q_t\) (mg g⁻¹) was calculated using equation (20) and the RR 195 adsorption capacity at equilibrium (after 24 h of stirring), \(q_e\) (mg g⁻¹) was calculated using equation (18)

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

where \(C_0\) and \(C_t\) (mg L⁻¹) are the RR 195 concentrations at initial and any time \(t\), respectively. \(V\) (L) is the volume of the solution, and \(m\) (g) is the mass of AC used.

Isotherm adsorption studies were carried out in the same procedure as determining the optimum AC dose and the pH experiment at four different temperatures (10, 20, 30, and 40 °C) by adding the optimized amount of AC sample in 100 mL of RR 195 solutions of different initial concentrations (100–350 mg L⁻¹) at the optimum pH. The equilibrium adsorption, \(q_e\) (mg g⁻¹), was calculated using equation (18).

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