CO₂-activated porous carbon derived from cattail biomass for removal of malachite green dye and application as supercapacitors

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Abstract

In this study, we developed a feasible and cost-effective method for obtaining porous carbon from cattail biomass as a promising material to be applied in various applications. The obtained carbon was further treated via CO₂ activation without any other chemical reagents. The results showed that the as-prepared activated carbon had a high specific surface area of 441.12 m²/g after CO₂ activation. Besides, the activated carbon showed excellent capacity to adsorb malachite green dye, and the effects of initial dye concentration, adsorption time, initial pH, and adsorption temperature were studied. Moreover, the activated carbon exhibited exceptional electrochemical performance as supercapacitors, with specific capacitance reaching 126.5 F/g at a current density of 0.5 A/g within a potential range of −1.0 to 0 V in a 6 M KOH solution. The excellent adsorption capacities and electrochemical performance suggested that the obtained activated carbon could be a promising candidate as an adsorbent and supercapacitor.

1. Introduction

Dyes are widely used in various industries such as textiles, paint, tanneries, plastics, rubber, pharmacies, electroplating, and food processing [1], and discharge of wastewater from these industries without proper treatment will result in severe environmental problems to aquatic animals and human beings [2]. Most of the synthetic dyes are harmful, thermally stable, and resistant to light, and are difficult to biodegrade owing to their complicated chemical structure [3]. As a result, in recent decades, there has been a growing demand for effective removal of these dyes from wastewater.

Malachite green (MG), a basic and cationic triphenylmethane dye, is widely utilized in dyeing of silk, cotton, wool, plastics, and paper, as well as in the fish industry as a biocide and medical disinfectant to control fungal and protozoan infections [2,4,5].
However, MG has been reported to produce many toxicological symptoms, including carcinogenicity, teratogenicity, mutagenicity, and pleural infections [6,7]. Therefore, effective removal of toxic MG from wastewater before discharging to the environment has been given more attention over the past few years.

Many approaches have been proposed for the removal of dyes from wastewater, such as adsorption [8], chemical coagulation [9], oxidation, ozonization [10], membrane separation [11], ion-exchange, and electrochemical treatments [9,12]. Among these techniques, adsorption using activated carbon is the most facile and effective method for the removal of noxious dyes from wastewater [13]. However, the usage of commercially available activated carbon from bituminous coal, lignite, and coconut shells has been limited owing to its high cost [14,15], thus leading to an urgent requirement for low-cost and effective raw materials for the production of activated carbon. Various materials, especially from agricultural wastes, ranging from bamboo, orange peel, oil palm fiber, rice bran, and coconut husk, have been employed for the production of activated carbon [16–20]. The activated carbon obtained from these materials have been noted to show excellent adsorption properties towards dyes such as methylene blue, MG, and Direct N Blue-106, which make them promising adsorbents for sewage treatment. In addition, it has also showed excellent electrochemical performance to be applied to supercapacitors. Activated carbon derived from biomass such as coconut fibers [21], corn stalk core [22] and potato waste residue [23] have been prepared and showed good electrochemical properties for supercapacitors. However, the chemical activation process was relatively complicated and the sewage (KOH and ZnCl₂) may do harm to the environment. Therefore, it is urgent to find a kind of low-cost raw material and facile preparation process to produce activated carbon for applications in supercapacitors.

Cattail is an aquatic plant mainly composed of lignocellulose, and is widely used in artificially constructed wetlands for the treatment of wastewater and polluted soil [24]. Cattail biomass is abundantly available in nature, and cattail fiber possesses a particular bamboo-like structure with a “n”-shaped gap in the middle part [25]. This unique structure of cattail provides a large specific surface area and forms an enclosed space, thus making it a good candidate for the production of adsorbents. However, to the best of our knowledge, there are only a few reports on the preparation of activated carbon from cattail for the adsorption of dyes and phenolic compounds [24,26]. Moreover, the available methods for the production of activated carbon involve complex chemical activation such as potassium hydroxide (KOH) activation or phosphoric acid (H₃PO₄) activation, after which, a subsequent washing process is required to adjust the pH of the product. Thus, a large quantity of water is needed and the generated sewage without proper treatment may result in serious environmental pollution, limiting the applications of these methods. Furthermore, there are only a few reports on the preparation of activated carbon from cattail fiber via a physical activation process.

Therefore, in the present study, cattail fiber derived activated carbon was prepared through a physical activation process using CO₂ as the activation gas without further treatment for the removal of MG from aqueous solution. The effects of contact time, initial dye concentration, solution pH, and temperature on the adsorption of the prepared activated carbon were studied. In addition, the equilibrium and kinetic data of the adsorption process were measured to investigate the adsorption isotherms, kinetics, and thermodynamics. Moreover, the potential application of the as-prepared activated carbon in supercapacitors was investigated using 6 M KOH solution as the electrolyte. The results obtained in this study are valuable for the multifunctional applications of the as-prepared activated carbon in dye removal and as supercapacitors.

2. Materials and methods

2.1. Materials

The cattail used in this study for the preparation of activated carbon was collected from a local pond in Daqing, China. Malachite green (MG) and potassium hydroxide (KOH) was purchased from Kermel LLC (Tianjin, China). Polytetrafluoroethylene (PTFE) was bought from Chenghexiang (Shenzhen, China), acetylene black was obtained from Tianyi LLC (Tianjin, China), and nickel foam was procured from Jiayisheng (Kunshan, China). All chemical reagents were of analytical grade and used as received without further purification.

2.2. Preparation of activated carbon

The collected cattails were washed with deionized water to remove soil and dust, and dried at 80 °C for 12 h to a constant weight for the removal of moisture and other volatile impurities. The dried cattails were then cut into pieces (1 cm in height and 1.5 cm in diameter) and stored in a desiccator. Carbonization was performed in a tube furnace under N₂ atmosphere. First, the cattails were heated from room temperature to 550 °C at a rate of 10 °C/min. Then, the samples were heated from 550 °C to 850 °C at a rate of 5 °C/min and maintained at 850 °C for 2 h to obtain carbon monolith. The obtained carbon monolith was further subjected to CO₂ activation. In this process, the carbon monolith was heated in the tube furnace from room temperature to 200 °C at a rate of 5 °C/min under pure CO₂ flow and kept at 200 °C for 2 h. Subsequently, the sample was heated from 200 °C to 800 °C at a rate of 3 °C/min and maintained at 800 °C for 2 h to obtain CO₂-activated carbon, denoted as CAC. The activation mechanism of CO₂ could be attributed to the chemical reaction: C(s) + CO₂ (g) → 2CO (g).

2.3. Adsorption experiments

MG solutions of various concentrations were prepared using distilled water. The pH of the dye solutions was adjusted using 0.01 M HCl or NaOH. The adsorption experiments were performed by adding 20 mg of CAC to 50 mL of MG solutions of various concentrations at specific pH and temperature in a thermostatic water bath on a rotary shaker at 140 rpm until the adsorption equilibrium was reached. After centrifugation for 15 min to remove CAC particles, the concentration of MG in the supernatant was determined using visible spectrophotometer at a wavelength of 619 nm. The amount of adsorbed MG was calculated based on the following equation:

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

where \( q_e \) is the amount of the absorbed dye (mg/g) at equilibrium, \( C_0 \) and \( C_e \) are the initial and residual concentrations of the dye at equilibrium (mg/L), respectively, \( V \) is the volume of the dye solution (L), and \( m \) is the mass of the adsorbent used (g). Each adsorption experiment was repeated for three times.

2.4. Thermal regeneration of CAC

Thermal regeneration of CAC was conducted after three regeneration cycles. In brief, 20 mg of CAC were added to 50 mL of MG solution (100 mg/L) in a conical flask and mechanically shaken for 12 h at 30 °C. Subsequently, the solution was filtered and the MG adsorption capacity was determined. The spent CAC was dried in an oven for 12 h and then placed in a tube furnace, heated from room temperature to 300 °C at a rate of 5 °C/min, maintained at 300 °C for 2 h, and allowed to cool to room temperature to obtain regenerated CAC.
2.5. Characterization of CAC

The surface morphology of the CAC samples was observed by scanning electron microscopy (SEM, FEI, Sirion, Japan) after sputter-coating the samples with a thin layer of gold. The pore-size distribution, mean pore diameter, total pore volume, and specific surface area of the samples were measured using N₂ adsorption analyzer (Maike, ASAP 2020, USA) based on Brunauer–Emmet–Teller (BET) and Barrett–Joyner–Halenda (BJH) methods at −196 °C.

2.6. Electrochemical measurements

The electrochemical measurements were conducted on an electrochemical workstation (CS350, Wuhan, China) in a three-electrode system with 6 M KOH solution serving as the aqueous electrolyte. The working electrode was prepared by loading a slurry containing 80 wt% CAC (about 4 mg), 10 wt% polytetrafluoroethylene (PTFE), and 10 wt% acetylene carbon black on a nickel foam substrate, followed by drying in an oven at 100 °C for 12 h and pressing the ensemble together under a pressure of 1 MPa. Ag/AgCl and Pt wire served as the reference and counter electrodes, respectively. The cyclic voltammogram (CV) curves were obtained in a potential range from −1.0 to 0 V by varying the scan rate from 5 to 100 mV/s. Galvanostatic charge/discharge (GCD) measurements were conducted in a potential window from −1.0 to 0 V under different current densities from 0.5 to 10 A/g. The electrochemical impedance spectroscopy (EIS) analysis was performed at the frequency range of 0.01 Hz–100 kHz with an amplitude of 5 mV. The specific capacitance \(C_s\) was calculated.

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**Fig. 1.** (a) SEM images of pristine cattail fibers at low magnification and (b) high magnification. (c) EDS spectrum of pristine cattail fibers. (d) SEM images of carbon at low magnification and (e) high magnification. (f) EDS spectrum of carbon. (g) SEM images of CAC at low magnification and (h) high magnification. (i) EDS spectrum of activated carbon.

**Fig. 2.** (a) The N₂ adsorption–desorption isotherm and (b) pore-size distribution of CAC.
from the discharge curves using the equation, \( C_s = \frac{(I \times \Delta t)}{(m \times \Delta V)} \), where \( I \) is the constant discharge current (A), \( \Delta t \) is the discharge time (s), \( m \) is the mass of electroactive materials (g), and \( \Delta V \) is the discharge voltage change (V).

3. Results and discussion

3.1. SEM observation

The structure and morphology of cattail fibers and CAC were characterized by SEM. As shown in Fig. 1, the surface of pristine cattail fibers was smooth and neat, barely with a split, and the fiber width was around 16.5 \( \mu \)m (Fig. 1a and b). After carbonization and activation, the strip fiber structure remained intact, but the fibers became irregular and wrinkled, and the width got reduced, which may be owing to the pyrolysis of biopolymers under high temperature after which the carbon framework was formed. The oxygen peaks in the EDS spectrum of carbon and CAC were reduced, which further indicated the decomposition of oxygen-containing functional groups in cattail fibers.

3.2. CAC porous structure characterization

The \( \text{N}_2 \) adsorption−desorption experiment was performed to characterize the pore structure of the CAC samples. The \( \text{N}_2 \) adsorption−desorption isotherm and corresponding pore-size distribution curve are presented in Fig. 2. The CA showed a type IV isotherm according to the IUPAC classification [27]. A H4-type hysteresis loop could be observed at a relative pressure \((P/P_0)\) range of 0.4–1.0 ascribed to capillary condensation, indicating the existence of mesopores in the CAC [28]. In addition, the CAC samples exhibited narrow BJH adsorption plots as shown in Fig. 2(b). The distribution of pore sizes in the range of 2.1–4.0 nm further illustrated that the CAC contained mesopores. The maximum specific surface area and pore volume were calculated as 441.12 m\(^2\)/g and 0.33 cm\(^3\)/g by the BET method, respectively. And the average pore diameter (BET) was less than 2.09 nm, indicating the mesopore character.

3.3. MG adsorption

3.3.1. Effect of contact time and initial MG concentration on MG removal

The effects of contact time and initial MG concentration on MG removal at \( 30 ^\circ C \) are shown in Fig. 3. The MG adsorption rate was rapid at the initial phase of 120 min, and thereafter became slower until equilibrium was reached and no more MG could be removed further. This may be attributed to the fact that at the beginning of adsorption, numerous surface sites are available for adsorption, which act as a high driving force for the transfer of MG [16]. However, after a lapse of time, the residual surface sites are difficult to be occupied, which may be owing to the repelling force between the solute molecules on the solid and bulk phases [29]. The adsorption capacity at equilibrium, \( q_e \), increased from 93.24 to 210.18 mg/g with an increase in the initial MG concentration from 40 to 100 mg/L. This is because the initial dye concentration provides a powerful driving force to overcome the resistance to mass transfer of the dye between the aqueous and solid phases [30], and the increase in initial MG concentration enhances the interaction between dye molecules and adsorbents. Therefore, MG adsorption increased with the increasing initial concentration of MG. Furthermore, it could also be clearly observed from Fig. 3 that the adsorption equilibrium was reached at around 240 min with the initial MG concentrations ranging from 40 to 80 mg/L. For 100 mg/L MG solutions, about 360 min was needed to reach equilibrium. Thus,
the experimental data was measured at 720 min to ensure that equilibrium was reached.

3.3.2. Effect of solution temperature on MG removal

The effect of solution temperature on MG removal by CAC is presented in Fig. 4. At the same initial MG concentration, the MG adsorption capacity of CAC slightly increased with the increasing temperature from 30°C to 60°C. The MG adsorption capacity slightly increased from 93.24 to 94.36 mg/g with the solution temperature increase from 30 to 60°C at MG concentration of 40 mg/g. But the MG adsorption capacity increased from 210.18 to 216.19 mg/g at MG concentration of 100 mg/g. A similar result on MG adsorption by activated carbon was reported by Onal et al. [9]. This effect of temperature on MG adsorption may be attributed to the endothermic nature of the adsorption reaction. At higher temperature, the dye molecules have more energy to interact with the active sites on the CAC surface. Moreover, the diffusion rate of the adsorbate molecules across the external boundary layer increases with the increase in solution temperature because of the decrease in the viscosity of the adsorbate solution [31].

3.3.3. Effect of solution pH on MG removal

The effects of initial pH of external solutions on the MG removal percentage are shown in Fig. 5. The MG removal percentage was found to significantly increase from 35.55% to 93.24% with the increase in solution pH from 2 to 8, which may be attributed to the increase in positive charges on the surface sites of the CAC and the decrease in adsorption at lower pH owing to electrostatic repulsive force. In addition, MG is a cationic dye, and the presence of considerable amount of H+ at lower pH may result in competition with dye cations for the adsorption sites of CAC, thus leading to a decrease in dye adsorption. However, no obvious change in the dye adsorption was observed at pH 8–12, which may be attributed to the increasing negative charge of the CAC surface at this pH leading to enhanced electrostatic force of the CAC surface towards positively charged dye cations [31].

3.3.4. Adsorption isotherms

The adsorption isotherms could illustrate the interactive behavior between the adsorbate in the solution and adsorbent at constant temperature under equilibrium condition. In the present study, the equilibrium data under different conditions were fitted with Langmuir and Freundlich isotherms. The linear form of Langmuir isotherm equation can be expressed as [24]:

\[
\frac{C_e}{q_e} = \frac{1}{q_m K_L} + \frac{C_e}{q_m}
\]

where \( q_e \) (mg/g) is the amount of dye adsorbed at equilibrium time, \( C_e \) (mg/L) is the equilibrium concentration of the dye solution, and
and $K_L$ (L/mg) are the maximum adsorption capacity and equilibrium adsorption constant related to the free energy of adsorption, respectively.

The logarithmic form of Freundlich adsorption isotherm can be given as [24]:

\[
\log q_e = \log K_F + \frac{1}{n} \log C_e
\]

(2)

where $K_F$ (L/mg) and $n$ are the isotherm constants that represent the capacity and intensity of the adsorption, respectively.

The fitted Langmuir and Freundlich plots and the corresponding isotherm parameters and correlation coefficients are shown in Fig. 6 and Table 1, respectively. It can be noted that the fitting to Langmuir isotherms was better, when compared with that to Freundlich isotherms. The higher values of $R^2$ from Langmuir model also confirmed that the adsorption was better represented by the Langmuir isotherm model, indicating that the process of adsorption was mainly monolayer. The values of $n > 1$ suggested a favorable adsorption on CAC [9]. Moreover, the adsorption capacities increased with increasing temperature, confirming that the adsorption process was endothermic. Table 2 shows the comparison of the maximum adsorption capacity of MG dye on activated carbon derived from various agricultural by-products. The as-prepared CAC in this study shows relatively higher MG dye adsorption than that reported in the previous works.

3.3.5. Adsorption kinetics

The Lagergren pseudo-first-order kinetics model, pseudo-second-order kinetics model, and intraparticle diffusion model were employed to investigate the adsorption kinetics. The Lagergren pseudo-first-order kinetics model was developed by Lagergren and Svenska [36] to predict the adsorption kinetics, and its linear form can be expressed as follows:

\[
\log (q_e - q_t) = \log q_e - k_1 t
\]

(3)

where $q_t$ and $q_e$ (mg/g) are the amounts of MG adsorbed at equilibrium and given time, respectively, and $k_1$ (min$^{-1}$) is the rate constant of pseudo-first-order adsorption.

The pseudo-second-order kinetic model was developed by Ho and Mckay [36] to predict the entire adsorption behavior, and its linear form can be given as follows:

\[
\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}
\]

(4)

where $k_2$ (g/mg/min) is the rate constant of second-order adsorption.

As shown in Fig. 7(a) and (b), the pseudo-second-order model showed good agreement with the experimental kinetics data, which could also be obtained from higher $R^2$ values as shown in Table 3. In addition, the adsorption capacities ($q_e$) calculated from the pseudo-second-order model were closer to the experimental values ($q_{e,exp}$), indicating that the pseudo-second-order kinetic model is more likely to describe the adsorption behavior of MG onto CAC.

However, as the two above-mentioned models could not sufficiently illustrate the diffusion mechanism during the adsorption process, the intraparticle diffusion model was employed to further analyze the adsorption process. The intraparticle diffusion can be expressed as follows:

\[
q_t = k_{ip} t^{1/2} + C_i
\]

(5)

where $C_i$ represents the intercept of stage i and $k_{ip}$ is the intraparticle diffusion rate constant (mg/g min$^{1/2}$), which can be obtained from the slope of the linear plots of $q_t$ versus $t^{1/2}$. It can be noted from the plots in Fig. 7(c) that the adsorption process comprised two stages and the plot was linear within a certain range, but non-linear over the entire time range, revealing that more than one model contributed to the adsorption mechanism with respect to the removal of MG by CAC. The initial linear portion might be owing to the electrostatic attraction between the dye and external surface of the adsorbent [31], and the second linear portion may be attrib-
uted to the gradual adsorption because of intraparticle diffusion [29]. As shown in Fig. 7(c), the linear lines in the second stage did not pass through the origin, which may be ascribed to the difference in the mass transfer rate between the initial and final stages of adsorption. Furthermore, the values of \( C \) increased with the initial MG concentration, indicating that boundary layer effect may be involved in the adsorption process [29].

### 3.3.6. Adsorption thermodynamics

The three thermodynamic parameters that must be considered during evaluation of the adsorption process are the free energy change (\( \Delta G^o \)), enthalpy (\( \Delta H^o \)), and entropy (\( \Delta S^o \)). The value of \( \Delta H^o \) and \( \Delta S^o \) can be obtained by van’t Hoff equation as follows:

\[
\ln K_c = \frac{\Delta S^o}{R} - \frac{\Delta H^o}{RT}
\]

where \( R \) (8.314 J/mol K) is the universal gas constant, \( T \) (K) is the absolute temperature, and \( K_c \) is the equilibrium constant. The \( K_c \) value can be calculated as:

\[
K_c = \frac{C_{Se}}{C_{ae}}
\]

where \( C_{ae} \) and \( C_{Se} \) are the equilibrium concentration of the dye on adsorbent (mg/L) and in solution (mg/L), respectively.

The values of \( \Delta H^o \) and \( \Delta S^o \) can be obtained from the slope and intercept of \( \ln K_c \) versus \( 1/T \), respectively, and \( \Delta G^o \) can be obtained from the following relation:

\[
\Delta G^o = -RT \ln K_c
\]

The \( \Delta G^o \), \( \Delta H^o \), and \( \Delta S^o \) values of adsorption are shown in Table 4. The positive value of \( \Delta H^o \) (4.93, 2.27, 6.66, 5.28 kJ/mol) confirmed that the adsorption process was endothermic in nature, which was consistent with the result obtained earlier demonstrating that the MG removal increased with increasing solution temperature. The positive value of \( \Delta S^o \) (38.00, 27.49, 37.90, 31.23 J/mol K) indicated increased randomness during the adsorption process [30]. In addition, the negative values of \( \Delta G^o \) (−4.19 to −7.74 kJ/mol) suggested the spontaneity of the adsorption process. Table 4 shows that the negative values of Gibbs free energy decreased with increasing the temperature, indicating the spontaneous nature and feasibility of the adsorption via physical forces as well as high tendency of adsorbent to the adsorbate [10]. Thus, higher temperature could promote the adsorption of MG, which is in accordance with the results of the adsorption isotherms.

### 3.4. Regeneration

Thermal regeneration of the spent activated carbon was performed after three cycles, and the value of adsorption capacity

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**Table 3**

<table>
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<tr>
<th>( C_0 ) (mg/L)</th>
<th>( q_e, \text{exp} ) (mg/g)</th>
<th>Lagergren-first-order kinetic model</th>
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<td>( q_e )</td>
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**Table 4**

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<th>( \Delta G^o ) (kJ/mol)</th>
<th>( \Delta H^o ) (kJ/mol)</th>
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was investigated. It can be seen from Fig. 8 that the adsorption capacity of CAC decreased from 210.18 to 148.51 mg/g after three regeneration cycles and the regeneration efficiency was 70.66%. This finding illustrated the efficacy of thermal treatment on the regeneration of dye-adsorbed CAC, suggesting that this method could also be applied for the regeneration of CAC used for the removal of other organic pollutants.

3.5. Electrochemical performance of CAC

To investigate the electrochemical performance of CAC, CV and GCD measurements were performed within the potential window of measurement in a 6 M KOH solution with a three-electrode system. The CV curves of the CAC samples were tested at scan rates from 5 to 100 mV/s, as shown in Fig. 9(a). It can be observed that the CV curves of the electrode displayed a nearly rectangular shape in a potential range from \(-1.0\) to \(0\) V, and maintained a quasi-rectangular shape even at a high potential scan rate of 100 mV/s, implying the formation of a perfect electrical double layer across the carbon network [37]. Furthermore, all of the discharge curves were almost symmetrical to the corresponding charge curves, revealing good electrochemical reversibility of the electrode. The GCD curves of the CAC electrodes at current densities ranging from 0.5 to 10 A/g are illustrated in Fig. 9(b). The five charge/discharge curves exhibited a quasi-triangular shape without obvious IR drop, which suggested the good capacitive behavior and electrochemical reversibility of the CAC samples [38]. The specific capacitance was calculated to be 126.5 F/g at a current density of 0.5 A/g. In addition, the charge/discharge time decreased with the current density ranging from 0.5 to 10 A/g, which may be ascribed to the fact that the electrolyte ions have sufficient time to enter and diffuse into the pores of the electrodes at lower current densities, when compared with that at higher current densities [23]. Table 5 shows the comparison of the specific capacitance of activated carbon derived from different biomass. Although the as-prepared CAC exhibits a relatively lower specific capacitance, it has a cost-effective and facile preparation compared with those in the literatures.

To further investigate the behavior of the as-prepared CAC electrode as a supercapacitor, the EIS analysis was performed in a 6 M KOH aqueous solution at a frequency range of 0.01 Hz–100 kHz. The Nyquist plots of the sample exhibited a linear trend at low frequency as shown in Fig. 9(d), indicating an ideal capacitive behavior of the electrodes [40]. At intermediate frequency, the inclined part of the curve (\(-45^\circ\)) was associated with Warburg impedance caused by the frequency dependence of ion diffusion/transport.

### Table 5

<table>
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<th>Electrode materials</th>
<th>Specific capacitance (F/g)</th>
<th>Activation method</th>
<th>Ref.</th>
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<td>KOH/ZnCl₂</td>
<td>[39]</td>
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<tr>
<td>Coconut fiber based activated carbon</td>
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<td>323</td>
<td>KOH</td>
<td>[22]</td>
</tr>
<tr>
<td>CAC</td>
<td>126.5</td>
<td>CO₂</td>
<td>This work</td>
</tr>
</tbody>
</table>
from the electrolyte to the electrode surface [41]. At high frequency, series resistance ($R_s$) was obtained from the intercept at the real axis (Z') in the Nyquist plot as shown in the inset of Fig. 9. The $R_s$ indicates the internal resistance of the electrodes and contact resistance at the interface of the active material/current collector [23], and the $R_q$ value of the CAC electrode was 1.53 $\Omega$, which revealed good ion transfer performance and excellent electronic conductivity of the sample.

4. Conclusions

In the present study, activated carbon derived from cattail fiber was prepared using a facile and cost-effective method and CO$_2$ activation process. The activated carbon exhibited a high specific surface area of 441.12 m$^2$/g after CO$_2$ activation for 2 h. Furthermore, the as-prepared activated carbon showed high MG adsorption capacity of 210.18 mg/g. Subsequently, the effects of initial dye concentration, solution pH, contact time, and temperature on MG adsorption were investigated. The adsorption process fitted well with the Langmuir model ($R^2 > 0.99$) as well as pseudo-second-order model ($R^2 > 0.98$). Further thermodynamic analysis indicated that the removal of MG from aqueous solution was a spontaneous and endothermic process. The activated carbon could be recycled using a thermal treatment method. Besides, the activated carbon showed good electrochemical performance as a supercapacitor, with specific capacitance reaching 126.5 F/g at a current density of 0.5 A/g within a potential range from −1.0 to 0 V. These results suggested that the activated carbon derived from cattail fiber could be a potential low-cost material for cationic dye removal and energy storage.

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References


