Three-dimensional hierarchical porous carbon derived from natural resources for highly efficient treatment of polluted water

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Abstract

Background: Dealing with the ever-increasing water pollution has become an urgent global problem, especially the organic containing polluted water. Physical adsorption has become one of the most popular ways for removal of organic dyes from wastewater due to its low cost as well as high efficiency. However, the adsorption performance is still limited by the low specific surface area (SSA) and unsuitable pore size. Hence, it is still a challenge to synthesize active carbon (AC) with high SSA, suitable pore size distribution as well as low cost for polluted water treatment. Here, we report an efficient method to prepare AC with large SSA from jujube for removal of both cationic dye and anionic dye from aqueous solution. The present results demonstrate that biomass-derived hierarchical porous carbon has a real potential application for wastewater treatment.

Results: The as-prepared hierarchical porous structure carbon material (PC-500-6) shows a high specific surface area (3203 $\text{m}^2/\text{g}$) and pore size distribution in the range 0.8 to 3.0 nm, while exhibiting an enhanced adsorption performance for both methylene blue (MB) and methylene orange (MO) from an aqueous solution. The maximum adsorption capacity even reaches 925.93 mg/g and 1281.39 mg/g for MB and MO, which was calculated from Langmuir model. Through analysis of the adsorption data, it was found that the corresponding adsorption kinetic fits the pseudo-second-order model very well.

Conclusions: It can be concluded that the adsorption of MB has a strong correlation with SSA, pore size distribution as well as the pore volume. The present study paved a practical way for wastewater treatment by using biomass-derived hierarchical porous carbon.

Keywords: Biomass materials, Porous carbon, Methylene blue, Methylene orange, Waste water

Background

With the rapid development of industrialization, water pollution has become an ever-increasing global concern up to now [1, 2]. More importantly, water pollution is becoming more and more serious due to the existence of organic dyes stemming from paper-making, leather, rubber and cosmetics [3]. Most of them not only cause serious environmental problems, but also threaten human life [4, 5]. Therefore, it is necessary to explore an environmentally friendly, low-cost and efficient method to remove organic dyes from contaminated water. In order to address this issue, various methods, such as chemical oxidation [6], photocatalysis [7–9], membrane filtration [10], and biological treatment have been proposed. However, the intrinsic limitations of these methods, such as high energy consumption, secondary pollution, and high cost have seriously hampered their...
practical applications. In contrast, physical adsorption has become one of the most popular ways for removal of organic dyes from wastewater due to its low cost as well as high efficiency [11–13]. Generally, activated carbon (AC) has been extensively used to treat polluted water owing to its high specific surface area (SSA) and high adsorption capacity [14–16]. Nevertheless, its adsorption performance is still poorer than expected due to the low SSA and unsuitable pore size. Hence, it is still highly desirable to produce AC with high SSA and suitable pore size distribution for polluted water treatment.

Biomass is considered as one of the potential raw materials to produce AC because of its abundance, well-organized porous structure and renewable characteristics [13, 17–19]. Recently, various biomass materials such as coconut shells, [20] palm jujube seed, [21] peanut shell, [22] bean husk, [23] mangosteen peel [24] and waste coffee grounds [25] have been used as precursors to prepare AC. However, the adsorption performance of state-of-the-art AC is still lower than as-expected due to the relatively low surface area and unsuitable pore size distribution. Here, we report an efficient method to prepare AC with large SSA from jujube for removal of both cationic dye and anionic dye in aqueous solution, such as MB and MO. In order to obtain porous carbon with large SSA and suitable pore size distribution, two parameters are needed to be optimized: carbonization temperature and activation agent. In this contribution, jujube was used as carbon precursor for the production of porous carbon due to its highly porous 3D interconnected structure with specific attention to controlling these two parameters. Because of the hierarchical porous structure, jujube-derived AC (PC-500-6) displays an excellent adsorption capacity as high as 925.93 mg/g and 1281.39 mg/g for MB and MO, which is one of the best reported results in the literature. Through analysis of the adsorption results, it was demonstrated that the adsorption of MB and MO fits the Langmuir model and pseudo-second order kinetic very well.

Materials and methods
Preparation of carbonized materials (C-X)
Fresh jujube was firstly washed with deionized water several times in order to remove dust and superficial impurities. Then the jujube was cut into thin sheets and frozen for 36 h. In the next step, the freeze-drying process was used to prepare dry samples through sublimating the ice in the jujube sheets at $T < -50 \degree C$ overnight. The carbonized jujube sheets were obtained through carbonization at 500 and 800 °C in Ar for 2 h with a heating rate of 10 °C/min, samples are marked as C–X ($X = 500$ or 800 °C).

Preparation of porous carbon materials (PC-X-Y)
For the preparation of AC samples, the mixture of C-X and KOH powder with a mass ratio of 1:Y was grinded ($Y = 2, 4$ and 6). The chemical activation was carried out by heating the mixture under Ar. Typically, the above mixture was placed in a tube furnace and heated to 800 °C with a heating rate of 10 °C/min and kept for 2 h at this temperature. After cooling down to room temperature, the carbon sample was taken out and treated with 1 M HCl. In the next step, the AC samples were filtered and washed several times with deionized water. Finally, purified AC samples were obtained and denoted as porous carbon (PC-X-Y) after drying at 80 °C in vacuum, where $X$ and $Y$ represents the carbonization temperature and the mass ratio of KOH/C–X, respectively.

Characterization
The morphology and surface element distribution of the porous carbon materials were characterized by field-emission scanning electron microscopy (SEM, XL30ESEM-FEG) with an acceleration voltage of 20 kV and energy-dispersive X-ray (EDX, OXFORD INSTRUMENTS X-MAX) mapping. Initially, the samples were coated with a thin gold layer before SEM measurements. The HRTEM images were collected on a high-resolution transmission electron microscope (HR-TEM, FEI G2 S-Twin transmission electron microscope operated at 200 kV). XRD patterns of the samples were obtained using X-ray diffraction (XRD, PANalytical Benchtop X-ray diffractometer) with Cu Kα radiation at 60 kV and 60 mA. Raman spectra of the carbon materials were measured on a Raman analyzer (Renishaw micro-Raman spectrometer (excitation-beam wavelength: 532 nm). The surface elemental composition was obtained by X-ray photoelectron spectroscopy (XPS) carried out on a VG ESCALAB MK II spectrometer using Al Kα radiation at 10.0 kV and 10 mA. The textural properties were measured by nitrogen adsorption/desorption at -196 °C on the Quantachrome Autosorb-1C-MS analyzer. The Brunauer–Emmett–Teller ( BET) method and density function theory (DFT) were utilized to calculate the SSA and PSD of the samples, respectively. Before the adsorption measurement, all samples were degassed at 200 °C for 12 h. The total pore volume was determined from nitrogen adsorbed at a relative pressure of $p/p_0 = 0.99$. All calculated data were derived from the $N_2$ isotherms when the test temperature was 0 °C.

Adsorption experiments
The adsorption of MB or MO from aqueous solution on the AC samples was performed in a batch process. Typically, 20.0 mg C-X or PC-X-Y was added into 50.0 ml MB
or MO solution with desired initial concentrations under stirring in a flask. The pH was adjusted with 0.1 M HCl or 0.1 M NaOH until it reached 6. After the equilibrium was reached, 1.0 ml of MB or MO solution was separated for subsequent analysis. The amount of MB or MO adsorption at equilibrium \( q_e \) was calculated by the following equation:

\[
q_e = \frac{(C_0 - C_e)V}{W},
\]

(1)

where \( C_0 \) and \( C_e \) (mg/l) are the liquid-phase concentration of MB before adsorption and at equilibrium, respectively. \( V \) (L) is the volume of the aqueous solution and \( W \) (g) is the mass of the adsorbent. The concentration of MB or MO was measured by UV–Vis–NIR spectrophotometry (Lambda 900, \( \lambda_{\text{max}} = 665 \pm 1 \text{ nm} \) or \( \lambda_{\text{max}} = 461 \pm 1 \text{ nm} \)). The experiments were repeated twice for reproducibility purposes.

Results and discussion

Physical structure

The surface structure and morphologies of the carbon samples were characterized by SEM and HRTEM, respectively. Figure 1a shows the SEM image of C-500, a cross-linked and microporous structure with open channel is clearly observed. After KOH activation, the porous carbons still remain with a 3D laminated structure as shown in Fig. 1b, c. The corresponding element mapping clearly shows the uniform distribution of carbon and oxygen element, which is shown in Additional file 1: Figure S1. HRETM was applied to give evidence of the morphology and structure of the carbon samples before and after activation in Fig. 1d–f. The carbon materials before and after activation are obviously different. The raw carbon material before activation is composed of mesopores and macropores, whereas the material after activation has more micropores. As shown in Fig. 1e, f, most of the regions consist of dark and light microstructures indicating that disordered graphitic structure and activation process produced more defects in AC samples. There are still graphitic layers with a spacing distance of 0.35 nm [26].

Material characterization

To determine the crystalline structure of the carbon materials, XRD patterns are recorded as displayed in Fig. 2a. There are two broad peaks at \( 2\theta = 26 \) and \( 43^\circ \) in C-500, which correspond to the (002) and (100) diffraction planes of graphitic carbon, respectively [27]. After chemical activation, significant changes in XRD files were observed for PC-500-Y. As shown in Fig. 2a, both peaks almost disappear when the mass ratio of KOH/carbon increases from 2 to 6, indicating KOH has destroyed the graphitic structure and more defects have been produced. The above results agree very well with the TEM analyses (Fig. 1e, f).
Raman spectroscopy can be employed to characterize the chemical structure of the carbon samples. As shown in Fig. 2b, there are two peaks located at 1350 cm\(^{-1}\) and 1580 cm\(^{-1}\) related to disordered carbon and \(E_2g\) mode of sp\(^2\)-hybridized graphitic carbon, respectively [28, 29]. The ratio of the D band to G band \((I_D/I_G)\) is commonly used to estimate the degree of disordering of the samples [30, 31]. The higher value of \(I_D/I_G\) indicates the presence of more defects in carbon samples. The \(I_D/I_G\) of C-500 is 1.05, which is much higher than that for PC-500-2 (0.84), PC-500-4 (0.82) and PC-500-6 (0.73), indicating that the chemical activation process led to more defects appearing in the samples.

The elemental composition of the carbon samples was estimated by XPS; the full survey spectrum and high-resolution XPS spectra of the samples are shown in Figs. 2c and 6b. There are three characteristic peaks at 285 eV, 400 eV and 531 eV, which correspond to C 1s, N 1s and O 1s, respectively. After KOH activation, nitrogen element almost disappears. As shown in Fig. 2d, the deconvolution of the C1s from PC-500-6 indicated the presence of –C=–C–, –C–OH, –C=O and –COOH; the corresponding peaks are located at 284.6 eV, 285.0 eV, 286.8 eV and 288.5 eV, respectively [32, 33]. In Fig. 6b, the O 1s spectrum consists of two peaks located at 533.7 eV and 532.3 eV, which correspond to O–C=O and –C–OH groups [34]. From XPS analyses, it was found that AC samples are mainly composed of carbon as well as a few functional groups on the surface of the samples.

The \(N_2\) adsorption/desorption technique was used to investigate the porosity properties of the samples: the corresponding parameters of the AC samples are summarized in Table 1. As shown in Fig. 3a, b, AC samples show a typical type-I isotherm with high adsorption capacity in the low relative pressure range (0–0.05), corresponding to the existence of micropores [35]. Moreover, the broadening of the adsorption knee in the relatively lower pressure range (0.05–0.4) suggested the
formation of mesopores during the activation process. The pore size distributions also confirmed the existence of the mesopores in the AC samples [36, 37]. As the mass ratio of KOH/C increases from 2 to 6, the adsorption knee becomes wider, indicating more mesopores are generated in PC-500-6. This conclusion is consistent with details of the porosity parameters of C-X and PC-X-Y in Fig. 3c, d and Table 1. It can be clearly observed that the values of SSA and percentage of $V_{0.8-3.0}$ in $V_{\text{total}}$ go up when the KOH/C mass ratio is enhanced. For example, $S_{\text{BET}}$ of PC-500-2, PC-500-4 and PC-500-6 is 2200, 3090 and 3203 m$^2$/g, respectively. In the same time, the value of $V_{0.8-3.0}/V_{\text{total}}$ increase from 53.2 to 86.9%.

### Table 1 Porosity properties of C-X and PC-X-Y samples

| Sample | $S_{\text{BET}}$ (m$^2$/g) | $V_{\text{total}}$ (cm$^3$/g) | $V_{0.8-3.0}$ | Average pore size (nm) |
|--------|----------------|-----------------|-------------|----------------|
| C-500  | 94            | 0.02            | 87.7%       | 4.3          |
| PC-500-2 | 2200         | 1.0             | 53.2%       | 1.8          |
| PC-500-4 | 3090         | 1.7             | 88.1%       | 2.00         |
| PC-500-6 | 3203         | 2.1             | 86.9%       | 2.45         |
| C-800  | 57            | 0.2             | 64.2%       | 10.1         |
| PC-800-2 | 1843         | 1.2             | 29.1%       | 1.8          |
| PC-800-4 | 2291         | 1.6             | 44.8%       | 1.9          |
| PC-800-6 | 2937         | 1.8             | 66.4%       | 2.3          |

* Specific surface area was calculated from BET method at $p/p_0 = 0.003–0.1$

* Total pore volume at $p/p_0 = 0.99$

* $V_{0.8-3.0}$ is the pore volume in the range of 0.8–3.0 nm

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**Fig. 3** N$_2$ adsorption/desorption isotherms of a C-500 and PC-500-Y, b C-800 and PC-800-Y. Pore size distribution of c C-500 and PC-500-Y, d C-800 and PC-800-Y
Adsorption isotherms

The adsorption isotherm describes how the interaction happens between AC samples and MB molecules the interface of liquid and solid phase during the adsorption process. In this article, three adsorption isotherms were used to analyze the adsorption data by nonlinear equations, such as Langmuir, Freundlich and Temkin isotherms.

The Langmuir model based on the assumption of monolayer adsorbates on a homogenous surface [10, 38] was tested. It is expressed by:

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

where \( K_L \) is the Langmuir adsorption constant (L/mg), and \( q_m \) is Langmuir monolayer adsorbate capacity (mg/g).

After linearization of the Langmuir isotherm Eq. (2), the linear equation is:

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

Multilayer adsorbates are described using the Freundlich model, which assumes an energetically heterogeneous surface. The Freundlich isotherm is represented by the following equation [39, 40]:

\[ q_e = K_F c_e^{1/n}, \]

where \( q_e \) is the equilibrium concentration of dye on the adsorbent (mg/g), \( c_e \) is the equilibrium concentration of dye in solution (mg/L), \( K_F \) and \( n \) are the Freundlich constants, which represent the adsorption capacity (mg/g) and the adsorption strength, respectively. The magnitude of \( 1/n \) quantifies the favorability of adsorption and the degree of heterogeneity of the adsorbent surface.

The well-known form of the Temkin isotherm indicates the effects of some indirect adsorbate/adsorbate interactions on adsorption isotherms, the isotherm can be expressed as:

\[ q_e = \frac{RT}{B_T} \ln(K_T c_e). \]

The linear form of the Temkin equation is: [41]

\[ q_e = B_T \ln K_T + B_T \ln c_e, \]

where \( B_T = R T / B_T \), \( T \) is the absolute temperature in K, \( R \) is the universal gas constant (8.314J/mol/K), \( K_T \) is the equilibrium binding constant (L/mg), and \( B_T \) is related to the heat of adsorption and constant value of Temkin isotherm.

Figure 4, Table 2, Additional file 1: Figure S5, Table S1 display the equilibrium adsorption data for C-X and PC-X-Y linearly fitted to Langmuir, Freundlich and Temkin isotherms and corresponding parameters, respectively. As shown in Fig. 4a, the amount of adsorbed MB increases at a low initial concentration and reaches a plateau at a high equilibrium concentration, indicating Langmuir isotherms fitted well with the experiment data [42]. It means that the adsorption took place at the specific homogenous sites within the carbon materials and MB molecules as a single monolayer [43]. According to Fig. 4b–d, the Langmuir isotherms exhibit higher correlation coefficients \((R^2 > 0.999)\) than Freundlich or Temkin model, indicating that Langmuir isotherm is a more precise model to describe the adsorption process. Moreover, maximum adsorption capacity is found to increase from 751.88 to 925.93 mg/g with the increase of mass ratio (KOH/carbon) from 2 to 6 (Table 2). Among all AC samples, PC-500-6 exhibits the highest adsorption capacity of MB (925.93 mg/g), more than 35 times higher than that of C-500. The adsorption results indicate that PC-500-6 delivers superior performance in dye adsorption compared to published results (Additional file 1: Table S2). In addition, optical photographs were taken before and after MB adsorption (Additional file 1: Figure S2a). For example, after the adsorption of MB with an initial concentration of 300 mg/L on PC-500-6, the polluted water became clear and colorless, which further revealed the efficient adsorption and distinct discoloration for wastewater using PC-500-6.

In order to investigate the adsorption kinetics of MB adsorption on AC, the experimental kinetic data are fitted to pseudo-first-order and pseudo-second-order kinetic models. The applied kinetic equations are as follows.

The pseudo-first-order kinetic model can be expressed as [44]:

\[ \ln(q_e - q_t) = \ln(q_e) - k_1 t, \]

where \( q_t \) is the amount of dye on the adsorbent at \( t \) min (mg/g), and \( k_1 \) is the rate constant of the pseudo-first-order kinetic model for the adsorption (min\(^{-1}\)). The values of \( q_e \) and \( k_1 \) can be determined from the intercept and the slope of the linear plot of \( \ln(q_e - q_t) \) versus \( t \), respectively. The pseudo-second-order kinetic model is represented by the following equation [45, 46]:

\[ \frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}, \]
where $k_2$ is the rate constant of the pseudo-second-order kinetic model for adsorption (g/mg/min). The slope and intercept of the linear plot of $t/q_t$ against $t$ yield the values of $q_e$ and $k_2$, respectively.

**Table 2**  Langmuir, Freundlich and Temkin isotherm parameters for C-500 and PC-500-Y for MB adsorption

| Isotherm | Parameter | C-500 | PC-500-2 | PC-500-4 | PC-500-6 |
|----------|-----------|-------|----------|----------|----------|
| Langmuir | $q_m$ (mg/g) | 26.39 | 751.88 | 877.19 | 925.93 |
|          | $K_L$ (L/mg) | 0.215 | 2.057 | 2.144 | 0.864 |
|          | $R^2$ | 0.99308 | 0.99998 | 0.99991 | 0.99964 |
| Freundlich | $1/n$ | -0.03491 | 0.03963 | 0.0659 |
|          | $K_F$ (mg/g(L/(mg)$^{1/n}$) | -628.4974 | 717.6759 | 665.6246 |
|          | $R^2$ | -0.76173 | 0.97225 | 0.98617 |
| Temkin    | $B_T$ | 23.52 | 29.79 | 50.56 |
|          | $K_T$(L/mg) | 1.07*10^9 | 1.52*10^8 | 2.83*10^4 |
|          | $R^2$ | 0.77325 | 0.98262 | 0.99095 |

Figure 5. Additional file 1: Figure S6 and Figure S7 display the kinetic curves and linear fits for the adsorption of MB by PC-X-Y at 20 °C using the pseudo-first-order and pseudo-second-order models. Table 3, Additional file 1: Tables S3, S4 present the coefficients for the pseudo-first-order and pseudo-second-order kinetic models. All the experimental data comply better with the pseudo-second-order kinetic model in terms of higher correlation coefficient values ($R^2 > 0.99$). This demonstrates that the pseudo-second-order kinetic model is more suitable to describe the adsorption behavior of MB by the PC-X-Y.

**Adsorption thermodynamics of the PC-500-6**

During the adsorption process, thermodynamic parameters are important in controlling the adsorption behavior. The adsorption free energy ($\Delta G$), the adsorption entropy ($\Delta S$), and the adsorption enthalpy ($\Delta H$) were calculated using Eqs. (10) and (11) expressed as follows:
where $q_e$ (mg/g) is the adsorption capacity, $C_e$ (mg/L) is the MB concentrations at equilibrium, $\Delta G$ (kJ/mol) is the standard Gibbs free energy change, $\Delta H$ (kJ/mol) is the standard enthalpy change, $\Delta S$ (J/mol K) is the standard entropy change, $R$ (8.314 J/mol/K) is the gas constant, and $T$ (K) is the absolute temperature.

The values of $\Delta G$, $\Delta H$ and $\Delta S$ were calculated and shown in Table 4. The negative enthalpy change ($\Delta H = -0.91$ kJ/mol) indicates that the adsorption reaction is an exothermic reaction, which is supported by the decreased adsorption capability with increasing of the temperature. The negative value of $\Delta G$ reveals that adsorption of MB onto membrane is a spontaneous and feasible process. The negative entropy change ($\Delta S = -2.56$ kJ/mol) indicates that the adsorption decreases randomly at the solid–solute interface during the adsorption. The thermodynamic calculations indicated that methylene blue adsorption was spontaneous and exothermic in nature.

Figure 6a shows clearly the linear relationship between $q_m$ and specific surface area ($S_BET$). It can be observed that the adsorption of MB has a strong correlation with SSA, indicating that SSA has a great impact on adsorption ability. For example, among all AC samples, PC-500-6 has the highest adsorption value of $917.43$ mg/g due to the highest SSA of $3203$ m²/g. Moreover, the pore volume and pore size distribution also have some influence on the adsorption capacity. In Table 1, AC samples with higher value of $V_{(0.8–3.0 \text{ nm})}/V_{\text{total}}$ have higher adsorption capacity. For example, PC-500-2, PC-500-4 and PC-500-6 show high adsorption values ($751.88, 884.96$ and $917.43$ mg/g) as well as high values of $V_{(0.8–3.0 \text{ nm})}/V_{\text{total}} (53.2\%, 88.1\%$ and $86.9\%)$. To understand the underlying mechanism more deeply, the molecular size of MB and pore size of AC are compared. As shown in Fig. 6c, the size of MB is

![Figure 5](image_url)  
**Fig. 5** Kinetic curves of (a) the pseudo-second-order kinetic model, (b) PC-500-Y for the adsorption of MB. (Experimental conditions: MB concentration was 250 mg/L for PC-500-2, 300 mg/L for PC-500-4 and PC-500-6 and adsorbent concentration was 20 mg/L.)

### Table 3 Kinetic parameters of the pseudo-second-order kinetic model for MB on PC-500-Y

| Absorbent | Slope | Intercept | $C_0$ (mg/l) | $q_e,\text{exp}$ (mg/g) | $q_e,\text{cal}$ (mg/g) | $k_2$ (g/mg/min) | $R^2$ |
|-----------|-------|-----------|-------------|------------------------|------------------------|-----------------|-------|
| PC-500-2  | 0.0016| 0.0034    | 250         | 616.27                 | 621.12                 | 7.60*10^-4      | 0.9997 |
| PC-500-4  | 0.0014| 0.0010    | 300         | 724.09                 | 724.647                | 2.07*10^-3      | 0.9999 |
| PC-500-6  | 0.0013| 0.0055    | 300         | 768.79                 | 781.25                 | 2.96*10^-4      | 0.9994 |

### Table 4 Thermodynamic parameters for the adsorption of MB on PC-500-6

| Absorbent | $t$ (°C) | $\Delta G$ (kJ/mol) | $\Delta H$ (kJ/mol) | $\Delta S$ (J/mol K) |
|-----------|----------|---------------------|---------------------|---------------------|
| PC-500-6  | 20       | $-1.07*10^4$        | $-0.91$             | $-2.56$             |
|           | 30       | $-9.45*10^3$        |                     |                     |
|           | 40       | $-7.17*10^3$        |                     |                     |

$$\ln \left( \frac{q_e}{C_e} \right) = -\frac{\Delta H}{RT} + \frac{\Delta S}{R},$$

$$\Delta G = \Delta H - T \Delta S,$$

where $q_e$ (mg/g) is the adsorption capacity, $C_e$ (mg/L) is the MB concentrations at equilibrium, $\Delta G$ (kJ/mol) is the standard Gibbs free energy change, $\Delta H$ (kJ/mol) is the standard enthalpy change, $\Delta S$ (J/mol K) is the standard entropy change, $R$ (8.314 J/mol/K) is the gas constant, and $T$ (K) is the absolute temperature.
about 0.7 nm × 1.6 nm, which can easily get into the pores with a diameter in the range of 0.8 nm to 3.0 nm. The dye adsorption capacity is also related to the pore volume of AC samples. As depicted in Table 1, the adsorption capacity increases as the pore volume was enhanced, such as the values of V_{total} for PC-500-2, PC-500-4 and PC-500-6 being 1.0, 1.7 and 2.1 cm³/g, and the corresponding adsorption values are 751.88, 884.96 and 917.43 mg/g, respectively. Based on above analyses, the adsorption capacity of AC is determined by three parameters: SSA, pore volume, and pore size distribution. The larger SSA provides more sites for the adsorption of MB molecules, and the suitable pore size distribution and large pore volume can also increase the adsorption capacity as well. Moreover, according to the high-resolution O 1s XPS spectra of PC-500-6, there were small quantities of oxygen-containing group on the surface of porous carbon. The presence of carboxylic and hydroxyl groups is considered to be good adsorption sites for cationic dyes driven by electrostatic interaction. The adsorption of MB dyes over the PC-500-6 adsorbent are collectively driven by the π–π interaction between the graphitic domains of carbon skeleton and aromatic rings of MB dye molecules, hydrogen linkages between the oxygen functionalities of PC-500-6 and nitrogen/oxygen centers in the dye molecules (Fig. 6c).

**Conclusions**

In summary, a 3D porous carbon was prepared from jujube at optimized carbonization temperatures and activation agent addition. The resulting 3D porous carbon shows a specific surface area (3203 m²/g) and suitable pore size distribution, leading to an excellent adsorption performance on both cationic dye and anionic dye from an aqueous solution, such as methylene blue (MB) and methylene (MO). PC-500-6 displays the high performance in adsorption MB and MO as high as 917.43 mg/g and 1281.39 mg/g, respectively. The present method paves a way to prepare biomass-derived AC for the removal of organic dyes from polluted water.
Abbreviations

MB: Methylene blue; MO: Methylene orange; SSA: Specific surface area;

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-021-00527-6.

Additional File 1: Figure S1. (a) SEM and (b–d) corresponding EDS Mapping images of PC-500-6 indicating the existence of C and O element. Figure S2. Photo of the (a) MB and (b) MO solutions before and after adsorption on the PC-500-6. Figure S3. Effect of (a) initial concentration (20 °C, 12 h, pH 6); (b) pH (Cp, 350 mg/L, 20 °C, 12 h); (c) adsorption temperature (Cp, 350 mg/L, 12 h, pH 6); (d) adsorption time (Cp, 350 mg/L, 20 °C, pH 6); (e) ion strength (Cp, 350 mg/L, 20 °C, 12 h, pH 6) and (f) the reusability (Cp, 350 mg/L, 20 °C, 12 h, pH 6) for MB adsorption on PC-500-6. Figure S4. The point of zero charge of PC-500-6. Figure S5. Equilibrium adsorption isotherms of (a) C-800; (b) PC-800-2; (c) PC-800-4 and PC-800-6; and (d) Langmuir, Freundlich and Temkin isotherms of MB on C-800 and PC-800-Y. (20 mg of C-800; PC-800-2 or PC-800-4/6 added to a 50 mL MB solution (10-80 mg/L, 100-500 mg/L or 150-550 mg/L) at a designated concentration after stirring for 12 h). Figure S5. The pseudo-first-order kinetic model of PC-500-Y for the adsorption of MB. (Experimental conditions: MB concentration = 250 mg/L for PC-500-Y, 300 mg/L for PC-500-4 and 500 mg/L for PC-500-6, and adsorbent concentration = 20 mg/L). Figure S7. (a) Kinetic curves; (b) pseudo first-order kinetic model and (c) the pseudo-second-order kinetic model of PC-500-Y for the adsorption of MB. (Experimental conditions: MB concentration = 250 mg/L for PC-500-2, 300 mg/L for PC-500-4 and 500 mg/L for PC-500-6 and adsorbent concentration = 20 mg/L). Figure S8. (a) Equilibrium adsorption isotherms; (b) Langmuir, Freundlich and Temkin isotherm parameters of C-800 and PC-800-Y for MB. Table S2. Comparison table of adsorption capacities of MB on different adsorbents. Table S3. Kinetic parameters of the pseudo-first-order kinetic model for MB on the PC-500-Y. Table S4. Kinetic parameters of the pseudo-second-order kinetic model for MB on the PC-500-Y. Table S5. Langmuir, Freundlich and Temkin isotherm parameters of PC-500-6 for MO.

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Authors’ contributions

JL conceived the idea, prepared, tested and wrote the manuscript. RH, SL and TT reviewed and corrected the manuscript. SM contributed with the surface chemistry analysis. SW and XC conceived the project and contributed to the writing of the manuscript. All authors reviewed the manuscript. All authors read and approved the final manuscript.

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Ethics approval and consent to participate

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Competing interests

The authors declare that they have no competing interest.

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