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# Biomass-derived O, N-codoped hierarchically porous carbon prepared by black fungus and *Hericium erinaceus* for high performance supercapacitor†

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Biomass-derived carbon materials have been widely researched due to their advantages such as low cost, environmental friendliness, readily available raw materials. Black fungus and *Hericium erinaceus* contain many kinds of amino acids. In this paper, unique O, N-codoped black fungus-derived activated carbons (FAC<sub>x</sub>), and *Hericium erinaceus*-derived activated carbons (HAC<sub>x</sub>) were prepared by KOH chemical activation under different temperatures without adding additional reagents containing nitrogen and oxygen functional groups, respectively. As electrode materials of symmetric supercapacitors, FAC<sub>2</sub> and HAC<sub>2</sub> calcined at 800 °C exhibited the highest specific capacitance of 209.3 F g<sup>-1</sup> and 238.6 F g<sup>-1</sup> at 1.0 A g<sup>-1</sup> in the two-electrode configuration with 6.0 M KOH as the electrolyte, respectively. The X-ray photoelectron spectroscopy confirmed that the as-synthesized FAC<sub>x</sub> and HAC<sub>x</sub> contained small amounts of nitrogen and oxygen elements. Moreover, heteroatom-doped FAC<sub>2</sub> and HAC<sub>2</sub> electrode materials shown excellent rate performance (84.1% and 75.0% capacitance retention at 20 A g<sup>-1</sup>, respectively). By comparison, the oxygen-rich hierarchical porous carbon (HAC<sub>2</sub>) shows higher specific capacitance and energy density and longer cycling performance. Nevertheless, carbon-rich hierarchical porous carbon (FAC<sub>2</sub>) indicates excellent rate performance. Biomass-derived heteroatom self-doped porous carbons are expected to become ideal active materials for high performance supercapacitor.

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## Introduction

With the rapid development of modern society, the increasing demand for renewable energy has stimulated great interest in electrochemical energy conversion and storage.<sup>1,2</sup> Supercapacitors are also called electrochemical capacitors, and are widely recognized as promising energy storage systems because of their unique properties such as high power density, fast charge–discharge rate, outstanding cycling stability and environmental friendliness. These advantages of supercapacitors can make up the shortage of conventional capacitors and batteries in many application fields.<sup>3,4</sup> Meanwhile, the

electrochemical performance of supercapacitors mainly depends on the electrode materials, and their physicochemical properties are a crucial and vital factor for supercapacitors. Therefore, searching for excellent electrode materials will greatly facilitate the future developments of supercapacitors.<sup>5–8</sup>

Carbon materials, conducting polymers<sup>9</sup> and metal oxides<sup>10</sup> as electrode materials of supercapacitors have been widely studied. Though conducting polymers and metal oxides have high theoretical specific capacitance due to their pseudocapacitance property, depending on the fast reversible redox reactions to storage energy,<sup>11</sup> the low conductivity and high cost are the main drawbacks of metal oxides, and the conducting polymers structure suffers repetitive swelling and shrinkage during the progress of charge–discharge, and results in the decrease of the capacity and cycle life.<sup>12</sup> However, carbon materials are the earliest and the most widely studied electrode materials of supercapacitors. According to the storage energy mechanism, carbon materials belong to electric double-layer capacitors (EDLC), whose storage energy depends on the ion absorption–desorption at the interface between the electrolyte and the electrode.<sup>13,14</sup> Although the low energy density and the low theoretical specific capacitance, these carbon-based materials including activated carbon, carbon nanotubes, graphene, carbon nanofiber, porous carbon and their derivatives exhibit excellent

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performance such as good conductivity, high thermal stability, high specific surface area, meanwhile the low cost and abundant resources of carbon have attracted many researchers concentrating on new carbon materials.<sup>15–19</sup>

Biomass materials have been widely selected as precursors to fabricate porous carbon materials with different morphologies for supercapacitors.<sup>20</sup> These biomass materials include rapeseed dregs,<sup>21</sup> loofah sponge,<sup>22</sup> willow catkin,<sup>23</sup> shiitake mushroom,<sup>24</sup> potato starch,<sup>25</sup> bamboo char,<sup>26</sup> bacterial cellulose,<sup>27</sup> walnut shell,<sup>28</sup> tobacco rods,<sup>29</sup> corn grain,<sup>30</sup> rice husk,<sup>31</sup> osmanthus flower,<sup>32</sup> peanut shell,<sup>33</sup> sunflower seed shell,<sup>34</sup> corncob,<sup>35</sup> cornstalk,<sup>36</sup> etc. Most biomass-derived carbon materials as mentioned above possess an excellent electrochemical capacitive performance. Cheng *et al.* reported a hierarchically porous carbon (the specific surface area reaches up to 2988 m<sup>2</sup> g<sup>-1</sup>) via H<sub>3</sub>PO<sub>4</sub> carbonization and KOH activation from natural shiitake mushroom for supercapacitor, which exhibits a specific capacitance of 306 F g<sup>-1</sup> at 1.0 A g<sup>-1</sup> in three-electrode cell with 6.0 M KOH as electrolyte and delivers a specific capacitance of 238 F g<sup>-1</sup> at 0.2 A g<sup>-1</sup> in a two-electrode cell.<sup>24</sup> Zou *et al.* prepared a high-performance porous carbon (the specific surface area is 1463 m<sup>2</sup> g<sup>-1</sup>) by KOH activation from osmanthus flower and applied it for supercapacitor, which displays the best specific capacitance of 255 F g<sup>-1</sup> at 1.0 A g<sup>-1</sup> in three-electrode cell using 6.0 M KOH as electrolyte.<sup>32</sup> Xu *et al.* improved an activated method of porous carbons derived from agricultural waste biomass corncobs via facile KOH solution soaking at room temperature prior to a one-step carbonization process.<sup>35</sup> The obtained porous carbon showed a high capacity of 394.9 F g<sup>-1</sup> at a current density of 1.0 A g<sup>-1</sup> in three-electrode system in a 6.0 M KOH aqueous electrolyte solution and the specific capacitance of the porous carbons-based supercapacitor measured under two-electrode configuration is 247 F g<sup>-1</sup> at 0.5 A g<sup>-1</sup>. Thus, hierarchical porous carbon can not only provide high specific surface area to store energy, but also shorten the diffusion distance of ions, which are beneficial to increasing the specific capacitance of supercapacitor.<sup>37</sup>

Furthermore, the electrochemical performance of porous carbon for supercapacitor usually could be improved by doping heteroatoms (*e.g.*, N, O and S atoms) in carbon framework. Especially, the oxygen and nitrogen functional groups can improve the surface wettability to promote the access of electrolyte and offer extra pseudocapacitance during charging and discharging process.<sup>38–42</sup> Therefore, developing a convenient method to prepare hierarchical porous carbon with suitable heteroatom functional groups is highly desirable for high performance supercapacitor.

Herein, we select black fungus and *Hericium erinaceus* containing rich protein and amino acid as resources of carbon to prepare oxygen and nitrogen codoped hierarchical porous carbon. In this work, black fungus-derived activated carbons (FAC<sub>X</sub>) and *Hericium erinaceus*-derived activated carbons (HAC<sub>X</sub>) were obtained by carbonization and KOH chemical activation under different temperature, respectively. The heteroatom-doped FAC<sub>2</sub> and HAC<sub>2</sub> calcined at 800 °C demonstrate porous 3D structure, moderate graphitization degree and satisfied specific surface area, meanwhile FAC<sub>2</sub> and HAC<sub>2</sub> as electrode materials of supercapacitor exhibit excellent electrochemical performance.

## Experimental

### Fabrication of carbon materials

The preparation process schematic of FAC<sub>X</sub> and HAC<sub>X</sub> porous activated carbons is demonstrated in Fig. 1. Firstly, the black fungus and *Hericium erinaceus* bought from the market were ground by crushing mill, then were washed with distilled water and dried at 80 °C in vacuum oven, successively. Secondly, the desiccated black fungus and *Hericium erinaceus* powders were put into tube furnace and treated at 500 °C for 60 min under Ar atmosphere with a heating rate of 5 °C min<sup>-1</sup>, respectively. The carbonized black fungus and *Hericium erinaceus* were washed with 1.0 M NaOH and 95% ethanol to remove metal ions and organic deposition within the products, respectively. The initial products were activated with KOH (KOH mixed with the initial product in a mass ratio of 3 : 1), then were calcined at 600 °C, 800 °C and 1000 °C with a heating rate of 2 °C min<sup>-1</sup> under Ar atmosphere for 120 min, respectively. Finally, these obtained coarse products were washed with 1.0 M HCl and distilled water to remove excess KOH and dried in vacuum oven for 24 h. The as-obtained products were denoted as FAC<sub>X</sub> and HAC<sub>X</sub>, where X = 1, 2 and 3 correspond to the temperature 600 °C, 800 °C and 1000 °C, respectively.

### Electrochemical measurement

The fabrication procedure of electrode materials is as follows: carbon materials, polytetrafluoroethylene and carbon black were mixed together in a mass ratio of 8 : 1 : 1. Then they were dispersed into ethanol, stirred and heated into paste, later the paste was crushed about a thickness of 150 μm, the sheet was cut into electrodes with a diameter of 12 mm and then was dried under vacuum at 60 °C overnight. Then the symmetric button-type supercapacitor was assembled with polypropylene membrane as separator.

All the electrochemical tests were performed at the voltage range of 0–1.0 V in 6.0 M KOH aqueous solution at room temperature. The specific capacitance of two-electrode configuration was calculated based on the discharge curve according to the following formulas:

$$C = \frac{I \Delta t}{\Delta V} \quad (1)$$

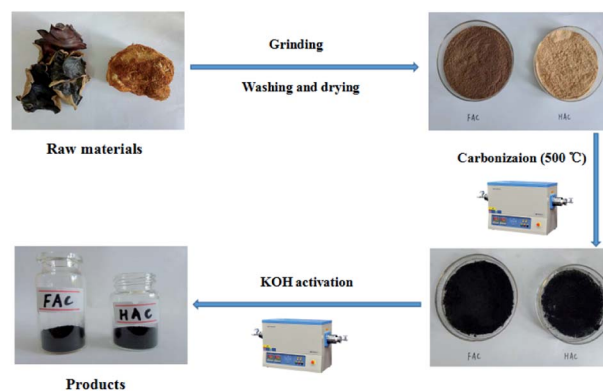


Fig. 1 Preparation process schematic of FAC<sub>X</sub> and HAC<sub>X</sub>.



$$\frac{1}{C} = \frac{1}{m_1 C_s} + \frac{1}{m_2 C_s} \quad (2)$$

where  $C$  and  $C_s$  represent the specific capacitance (F) and single electrode specific capacitance ( $\text{F g}^{-1}$ ), respectively,  $I$  is the discharge current (A),  $\Delta t$  is the discharge time (s),  $\Delta V$  corresponds to the potential window (V),  $m_1$  and  $m_2$  represent the mass (g) of active material on two electrodes.

The energy density and power density of supercapacitor were calculated according to the following formulas:

$$E = \frac{1}{8 \times 3.6} C_s V^2 \quad (3)$$

$$P = \frac{E}{\Delta t} \quad (4)$$

where  $E$  and  $P$  represent energy density ( $\text{W h kg}^{-1}$ ) and power density ( $\text{W kg}^{-1}$ ), respectively,  $C_s$  is the single electrode specific capacitance ( $\text{F g}^{-1}$ ) of the supercapacitor,  $V$  is the voltage range (V),  $\Delta t$  is the discharge time (h).

## Results and discussion

### Materials characterization

The morphologies of  $\text{FAC}_X$  and  $\text{HAC}_X$  are demonstrated in Fig. 2. It is apparent that activation temperature has a great influence on morphology and pore size of as-prepared carbon materials. There are only some shallow pores on the surface of bulk and thick  $\text{FAC}_1$  (shown in Fig. 2a) and  $\text{HAC}_1$  (shown in Fig. 2d), which the initial products were activated at  $600^\circ\text{C}$ . When the activation temperature increased to  $800^\circ\text{C}$ , the as-obtained  $\text{FAC}_2$  (shown in Fig. 2b) and  $\text{HAC}_2$  (shown in Fig. 2e) emerge more pores,  $\text{HAC}_2$  possesses more abundant pores with different sizes than  $\text{FAC}_2$  and presents distinct three-dimensional network. From Fig. 2c and f, we can observe that more nano graphite sheets appear with the further increase of activation temperature to  $1000^\circ\text{C}$ , which indicates that part of the bulk carbon matrix converted to flake graphite carbon.<sup>43</sup>  $\text{FAC}_3$  has large and folded graphite carbon layers with some pores, and  $\text{HAC}_3$  has more graphite carbon fragments and pores. These unique structures are useful for forming a double-layer interface between electrode and electrolyte solution, which benefit for the rapid diffusion of electrolyte ions from the

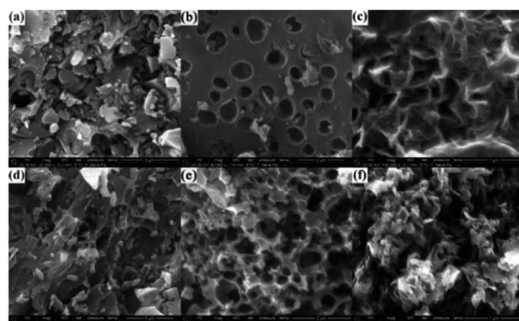


Fig. 2 SEM images of (a)  $\text{FAC}_1$ , (b)  $\text{FAC}_2$ , (c)  $\text{FAC}_3$ , (d)  $\text{HAC}_1$ , (e)  $\text{HAC}_2$  and (f)  $\text{HAC}_3$ .

surface into the interiors of  $\text{FAC}_X$  and  $\text{HAC}_X$  electrodes and reducing the resistance during the charge–discharge process.

The nitrogen adsorption and desorption isotherms of  $\text{FAC}_X$  and  $\text{HAC}_X$  are shown in Fig. 3a and c. It is obvious that the isotherm of  $\text{FAC}_1$  belongs to the type-I, which means a typical microporous material, and the specific surface area of  $\text{FAC}_1$  is  $363.5 \text{ m}^2 \text{ g}^{-1}$ , the average pore diameter is  $0.889 \text{ nm}$ . When the activation temperature reached at  $800^\circ\text{C}$  or  $1000^\circ\text{C}$ , the isotherms of  $\text{FAC}_2$  and  $\text{FAC}_3$  change to the combination of type-I curve and type-IV curve, which show typical feature of micropores and mesopores. It demonstrates that the two materials consist of both microporous structure and mesoporous structure,<sup>44</sup> the specific surface area of  $\text{FAC}_2$  and  $\text{FAC}_3$  are  $1227.3 \text{ m}^2 \text{ g}^{-1}$  and  $1501.6 \text{ m}^2 \text{ g}^{-1}$ , respectively, corresponding average pore size are  $1.278 \text{ nm}$  and  $1.332 \text{ nm}$ . However,  $\text{HAC}_X$  materials all present the combined I/IV type isotherms, which are different from that of  $\text{FAC}_X$ . And the specific surface area of  $\text{HAC}_1$ ,  $\text{HAC}_2$  and  $\text{HAC}_3$  are  $957.2 \text{ m}^2 \text{ g}^{-1}$ ,  $1362.0 \text{ m}^2 \text{ g}^{-1}$  and  $1667.5 \text{ m}^2 \text{ g}^{-1}$ , respectively, which are higher than that of  $\text{FAC}_X$ . Their corresponding average pore diameters are  $1.030 \text{ nm}$ ,  $1.186 \text{ nm}$  and  $1.352 \text{ nm}$ , respectively. These materials, except  $\text{FAC}_1$ , possess interconnected hierarchical porous structure, which is beneficial to improving the supercapacitive performance. Studies have shown that micropores can offer a larger specific surface area to absorb electrolyte ions, mesopores can be used as rapid channels for ionic diffusion.<sup>39</sup>

The pore size distribution (shown in Fig. 3b and d) was obtained by DFT method. It is apparent that the pore size distributions of  $\text{FAC}_1$  and  $\text{HAC}_1$  are mainly focused on the range of microporous (below  $2 \text{ nm}$ ), while  $\text{FAC}_2$ ,  $\text{FAC}_3$ ,  $\text{HAC}_2$  and  $\text{HAC}_3$  possess some small mesoporous, which are distributed at around  $2\text{--}4 \text{ nm}$ . In addition, the values of specific surface area and pore volume of  $\text{FAC}_X$  and  $\text{HAC}_X$  samples are showed in Table S1 (ESI<sup>†</sup>). According to these results, it can be seen that with the activation temperature increasing from  $600^\circ\text{C}$  to  $1000^\circ\text{C}$ , the BET area, micropore area, total pore volume and mesoporous number of  $\text{FAC}_X$  and  $\text{HAC}_X$  samples increase gradually,  $\text{FAC}_3$  and  $\text{HAC}_3$  possess the maximum specific

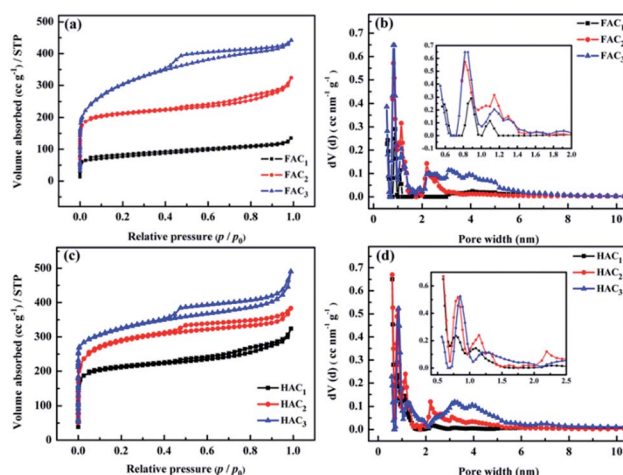


Fig. 3 (a and c)  $\text{N}_2$  adsorption–desorption isotherms and (b and d) pore size distributions of  $\text{FAC}_X$  and  $\text{HAC}_X$ .



surface area of  $1501.6 \text{ m}^2 \text{ g}^{-1}$  and  $1667.5 \text{ m}^2 \text{ g}^{-1}$ , respectively. Though the average pore diameter of  $\text{HAC}_2$  is smaller than that of  $\text{FAC}_2$ , the specific surface area and pore volume of  $\text{HAC}_2$  are higher than that of  $\text{FAC}_2$ . The high specific surface area and suitable number of microporous and mesoporous have a crucial effect on supercapacitor energy storage.<sup>45,46</sup> The rich pore structure provides more active sites and electron transport channels for electrolyte ions, meanwhile improves the utilization rate of the active substance of the electrode. The hydrated cations such as  $\text{K}^+$  and  $\text{H}^+$  can easily get through these unique channels and contribute to energy storage because the sizes of bare and hydrated cations of electrolytes are smaller than  $1 \text{ nm}$ .<sup>47</sup> Therefore, it is predicted that the  $\text{HAC}_2$  may exhibit better electrochemical capacitance than other samples because of the smaller pore size, the higher specific surface area and higher micropore volume as well as suitable mesopore.<sup>32</sup>

The crystal structures of  $\text{FAC}_X$  and  $\text{HAC}_X$  were further confirmed by XRD analysis and are displayed in Fig. 4a and b. It is obvious that the prepared carbon materials all present characteristic graphitic peaks located at around  $24.7^\circ$  and  $43.7^\circ$ , which can be ascribed to C (002) and C (101) plane reflection,<sup>16,21,48,49</sup> respectively. The high intensity in the low angle region indicates higher graphitization degree, which may be ascribed to the existence of the abundant micropores in all the samples,<sup>49</sup> is consistent with the  $\text{N}_2$  sorption results. From Fig. 4a, the peaks of  $\text{FAC}_2$  are very sharper, suggesting that its crystalline and graphitization degree improve. But the lower and enlarged width of peaks of  $\text{FAC}_1$  and  $\text{FAC}_3$  implies more amorphous nature of samples. In contrast with  $\text{FAC}_X$ , the C (002) peaks at around  $24.7^\circ$  of  $\text{HAC}_X$  resemble each other in shape. However, the peak at  $43^\circ$  of  $\text{HAC}_X$  is weakened gradually when the activation temperature became from  $600^\circ \text{C}$  to  $1000^\circ \text{C}$ , suggesting that the amorphous of  $\text{HAC}_X$  increased with the increasing of activation temperature.

The graphitic structure of  $\text{FAC}_X$  and  $\text{HAC}_X$  was also characterized by Raman spectra (shown in Fig. 4c and d). Two featured peaks at around  $1340 \text{ cm}^{-1}$  (D-band) and  $1600 \text{ cm}^{-1}$  (G-band)

can be observed among all of these carbon materials, which are attributed to the defective carbon crystallites and the vibration of  $\text{sp}^2$  carbon atoms,<sup>50</sup> respectively. It is interesting that  $\text{FAC}_3$  and  $\text{HAC}_3$  are detected second-order 2D peaks at around  $2700 \text{ cm}^{-1}$ . The 2D-band is sensitive to the number of graphene layers, indicating that the two materials possess a few well-graphitized layers. The relative intensity ratio of D-band to G-band ( $I_D/I_G$ ) is extensively adopted to evaluate the graphitization degree of carbon materials; the lower  $I_D/I_G$  value signifies the higher graphitization degree of the materials.<sup>51</sup> It can be calculated that the  $I_D/I_G$  values of  $\text{FAC}_1$ ,  $\text{FAC}_2$  and  $\text{FAC}_3$  are 0.87, 0.77 and 0.76, respectively, meanwhile  $I_D/I_G$  values of  $\text{HAC}_1$ ,  $\text{HAC}_2$  and  $\text{HAC}_3$  are 0.90, 0.81 and 0.27, which indicate that the obtained carbon materials treated with higher activation temperature own better graphitization degree and lower crystal defects. The defect of hierarchical porous carbon can improve wettability, whereas carbon with the high graphitization degree can deliver a satisfying electrical conductivity and outstanding chemical stability. Hierarchical porous carbon with moderate  $I_D/I_G$  values may show high supercapacitive performance.

X-ray photoelectron spectroscopy (XPS) was carried out to analyze the main element and content of as-prepared  $\text{FAC}_2$  (shown in Fig. 5a) and  $\text{HAC}_2$  (shown in Fig. 5b). Three peaks concentrated at about 284.6, 401.0 and 533.2 eV are detected in the general spectroscopy, the values of these binding energy are corresponded to C 1s, N 1s and O 1s element, respectively. The fitting result of the spectrum indicates that  $\text{FAC}_2$  mainly contains carbon ( $\sim 88.38 \text{ at}\%$ ) along with few amount of

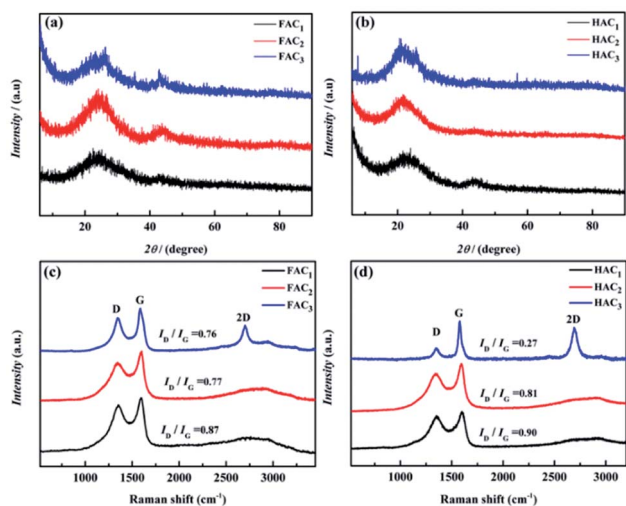


Fig. 4 X-ray diffraction pattern of (a)  $\text{FAC}_X$  and (b)  $\text{HAC}_X$ , and Raman spectroscopy of (c)  $\text{FAC}_X$  and (d)  $\text{HAC}_X$ .

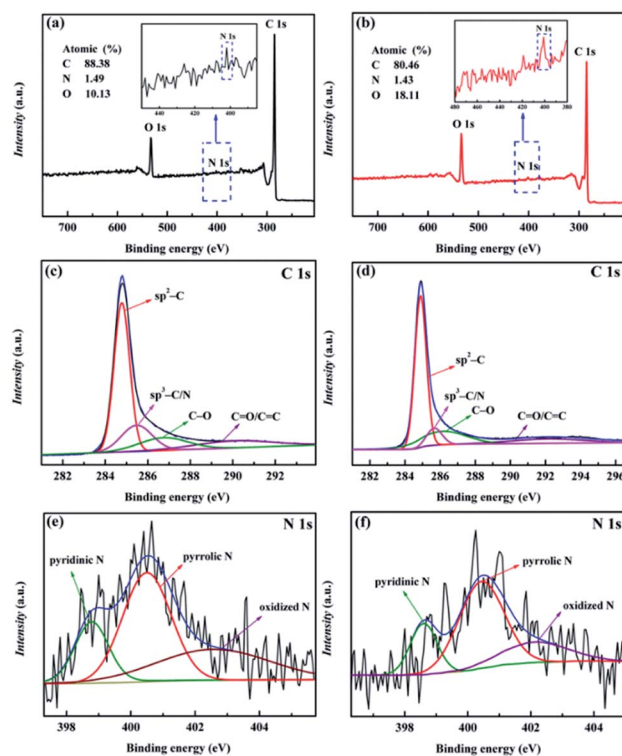


Fig. 5 XPS spectra of (a)  $\text{FAC}_2$  and (b)  $\text{HAC}_2$ ; (c) C 1s and (e) N 1s of  $\text{FAC}_2$ ; (d) C 1s and (f) N 1s of  $\text{HAC}_2$ .



nitrogen ( $\sim 1.49$  at%) and oxygen ( $\sim 10.13$  at%), while the corresponding element content of HAC<sub>2</sub> are 80.46 at%, 1.43 at% and 18.11 at%, respectively, indicating that the N element content of HAC<sub>2</sub> is almost equal to that of FAC<sub>2</sub> and the O element content of HAC<sub>2</sub> is higher than that of FAC<sub>2</sub>. Fig. 5c and d show the C 1s spectra of FAC<sub>2</sub> and HAC<sub>2</sub>, respectively. Both of them are differentiated into four peaks, which include sp<sup>2</sup>-C peak at 284.6 eV, sp<sup>3</sup>-C/N peak at 285.6 eV, C–O peak at 286.6 eV and C=O/C=C peak at 289.8–291.8 eV, respectively. Furthermore, the N 1s spectra of FAC<sub>2</sub> and HAC<sub>2</sub> are shown in Fig. 5e and f, respectively, whose peaks located at 398.4, 400.3 and 402.7 eV can be assigned to pyridinic N (N-6), pyrrolic N (N-5) and oxidized N (N-X), which may be the decomposition product of organic ingredients. It is well known that oxygen and nitrogen functionalities could upgrade the surface wettability of carbon materials to facilitate the access of electrolyte and be involved in the faradaic reactions that enhance the pseudocapacitance of supercapacitor, which result in the better electrochemical performance.

### Electrochemical performance characterization

The electrochemical properties of the prepared FAC<sub>X</sub> and HAC<sub>X</sub> electrodes were respectively investigated under a two-electrode configuration with 6.0 M KOH aqueous solution as electrolyte. The CV curves of FAC<sub>X</sub> and HAC<sub>X</sub> measured at a sweep rate of 50 mV s<sup>-1</sup> are shown in Fig. 6a and 7a. In Fig. 6a, it is obvious that the CV profiles of FAC<sub>2</sub> electrode displays nearly rectangular, and the CV curve of FAC<sub>2</sub> exhibits great current response and displays the largest area among the FAC<sub>X</sub>, indicating that FAC<sub>2</sub> possesses higher capacitance than FAC<sub>1</sub> and FAC<sub>3</sub>. Moreover, there are no significant changes of rectangular characteristic of FAC<sub>2</sub> (shown in Fig. 6b) with the scan rate increasing from 5 mV s<sup>-1</sup> to 50 mV s<sup>-1</sup>. These indicate that FAC<sub>2</sub> demonstrates better electrical double layer capacitor (EDLC)

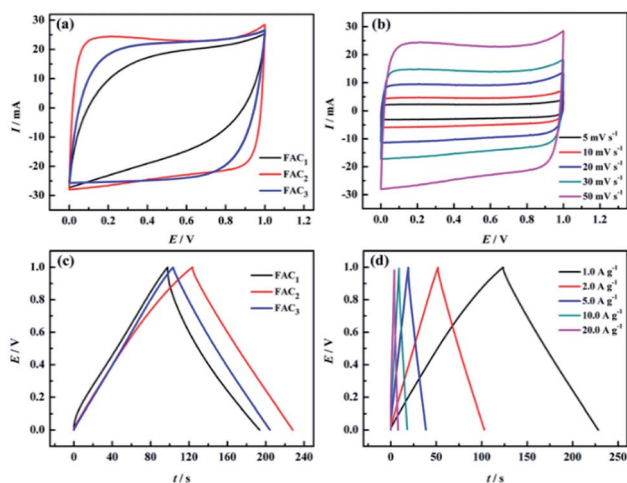


Fig. 6 Electrochemical performance of FAC<sub>X</sub> measured in two-electrode system in 6.0 M KOH electrolyte. (a) CV curves of FAC<sub>1</sub>, FAC<sub>2</sub> and FAC<sub>3</sub> at 50 mV s<sup>-1</sup>; (b) CV curves of FAC<sub>2</sub> at different scan rates; (c) GCD curves of FAC<sub>1</sub>, FAC<sub>2</sub> and FAC<sub>3</sub> at 1.0 A g<sup>-1</sup>; (d) GCD curves of FAC<sub>2</sub> at different current densities.

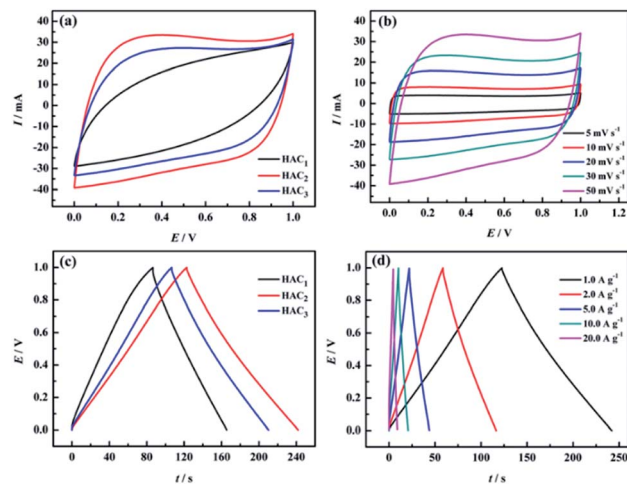


Fig. 7 Electrochemical performance of HAC<sub>X</sub> measured in two-electrode system in 6.0 M KOH electrolyte. (a) CV curves of HAC<sub>1</sub>, HAC<sub>2</sub> and HAC<sub>3</sub> at 50 mV s<sup>-1</sup>; (b) CV curves of HAC<sub>2</sub> at different scan rates; (c) GCD curves of HAC<sub>1</sub>, HAC<sub>2</sub> and HAC<sub>3</sub> at 1.0 A g<sup>-1</sup>; (d) GCD curves of HAC<sub>2</sub> at different current densities.

behaviour and excellent electrochemical reversibility during the stage of charge–discharge.<sup>52</sup> By contrast, the shapes of CV curves of HAC<sub>X</sub> (shown in Fig. 7a) measured at a sweep rate of 50 mV s<sup>-1</sup> exhibit some similar and different characteristics from FAC<sub>X</sub>, the CV profiles of HAC<sub>2</sub> and HAC<sub>3</sub> are quite similar to the rectangle profile of FAC<sub>3</sub> and are different from that of FAC<sub>2</sub>, and HAC<sub>2</sub> also displays the largest area among the HAC<sub>X</sub> materials. The elliptical shape of FAC<sub>1</sub> and HAC<sub>1</sub> indicates that they remain charge transfer resistance during the charge–discharge progress.<sup>53</sup> In addition, above results suggest that FAC<sub>2</sub> and HAC<sub>2</sub> fabricated at 800 °C exhibit better capacitance properties than those carbon materials fabricated at 600 °C or 1000 °C.

The galvanostatic charge–discharge (GCD) curves of FAC<sub>X</sub> (shown in Fig. 6c) and HAC<sub>X</sub> (shown in Fig. 7c) electrodes were measured at 1.0 A g<sup>-1</sup>. All curves show an approximate isosceles triangle shape, which indicate excellent Coulomb efficiency and electrochemical reversibility at the stage of charge–discharge.<sup>54</sup> There are small voltage drops observed from GCD curves among of these electrode materials, indicating a low equivalent series resistance of FAC<sub>X</sub> and HAC<sub>X</sub>. It can be seen that the voltage drops of FAC<sub>2</sub> (shown in Fig. 6d) and HAC<sub>2</sub> (shown in Fig. 7d) continually rise along with the current density increase from 1.0 A g<sup>-1</sup> to 20 A g<sup>-1</sup>, which can be explained as follows: during the progress of charge–discharge the electrolyte ions will transport from the surface of electrode into the inner of electrode, at this time, the pore structure and pore size of electrode material make great influence on electrolyte ions, narrow pore diameter will greatly obstruct electrolyte ions to access to inner of electrode with the current intensity increase, thus result in larger voltage drops.<sup>55</sup> In addition, the GCD curves of FAC<sub>2</sub> and HAC<sub>2</sub> display longer discharge time than other prepared materials at 1.0 A g<sup>-1</sup>, indicating that the two electrode materials exhibit higher specific capacitance, the corresponding specific capacitance of FAC<sub>2</sub> and HAC<sub>2</sub> calculated following



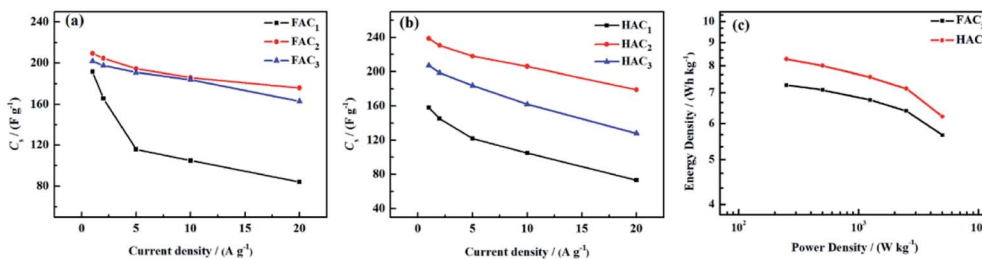


Fig. 8 Specific capacitance of (a)  $\text{FAC}_x$  and (b)  $\text{HAC}_x$  at different current densities; (c) Ragone plot of  $\text{FAC}_2$  and  $\text{HAC}_2$ .

above formula (1) and (2) are  $209.3 \text{ F g}^{-1}$  and  $238.6 \text{ F g}^{-1}$ , respectively, which are higher than the values of commercial carbon materials ( $132 \text{ F g}^{-1}$  at  $0.2 \text{ A g}^{-1}$ )<sup>24</sup> and can be compared with some reported biomass carbon materials. The comparison of specific capacitance of some reported biomass-based carbon materials are listed in Table S2.†

Based on the discharge curves of those electrode materials, the specific capacitance values of  $\text{FAC}_x$  and  $\text{HAC}_x$  electrodes are also calculated following above formula (1) and (2), these results are given in Fig. 8a and b. The detailed data are shown in Table 1. Among  $\text{FAC}_x$  materials (shown in Fig. 8a)  $\text{FAC}_2$  displays the highest specific capacitance and excellent rate performance, the specific capacitance of  $\text{FAC}_2$  is 209.3, 204.6, 194.5, 186.0 and  $176.0 \text{ F g}^{-1}$  at current densities of 1.0, 2.0, 5.0, 10, 20  $\text{A g}^{-1}$ , respectively. Its capacitance retention is 84.1% when the current density increases from  $1.0 \text{ A g}^{-1}$  to  $20 \text{ A g}^{-1}$ . And the specific capacitance values of  $\text{FAC}_3$  are close to that of  $\text{FAC}_2$  at the corresponding current densities, the specific capacitance of  $\text{FAC}_3$  decrease from  $201.8 \text{ F g}^{-1}$  to  $163.0 \text{ F g}^{-1}$  with the capacitance retention of 80.8%. The specific capacitance of  $\text{FAC}_1$  decays quickly with the increasing of current density. Compared with  $\text{FAC}_x$ , the highest specific capacitance value of  $\text{HAC}_2$  electrode is  $238.6 \text{ F g}^{-1}$  at  $1.0 \text{ A g}^{-1}$ , higher than the specific capacitance of  $158.3 \text{ F g}^{-1}$  and  $207.2 \text{ F g}^{-1}$  of  $\text{HAC}_1$  and  $\text{HAC}_3$ , respectively. Meanwhile the capacitance retention of  $\text{HAC}_1$ ,  $\text{HAC}_2$  and  $\text{HAC}_3$  are 46.1%, 75.0% and 61.8% at  $20 \text{ A g}^{-1}$ . It is apparent that  $\text{FAC}_2$  electrode shows the most excellent rate performance among  $\text{FAC}_x$  electrodes, and  $\text{HAC}_2$  electrode displays more excellent rate performance than other prepared  $\text{HAC}_x$  electrodes. These results are ascribed to their unique O, N-codoped hierarchical pore structures of  $\text{FAC}_2$  and  $\text{HAC}_2$  materials, which have more reactive sites and conductive network providing more conductive channels and shortening the electrolyte ion transport path.<sup>49</sup> The specific

capacitance of  $\text{HAC}_2$  electrode is higher than that of  $\text{FAC}_2$  electrode, which is ascribed to the higher content of oxygen element for  $\text{HAC}_2$ . The more oxygen functional groups can offer extra pseudocapacitance. It is interesting that  $\text{FAC}_2$  containing rich carbon element shows better rate performance than  $\text{HAC}_2$ . This may be the reason that the construction of  $\text{HAC}_2$  possessing more defective carbon crystallites is easy to be destroyed under the high current density.

The energy density and power density are important parameters for evaluating the performance of supercapacitors. According to above formula (3) and (4), the energy density and power density values of  $\text{FAC}_2$  and  $\text{HAC}_2$  electrodes are calculated, and the Ragone plot is shown in Fig. 8c. It can be seen that the maximum energy densities of  $\text{FAC}_2$  and  $\text{HAC}_2$  are  $7.3 \text{ W h kg}^{-1}$  and  $8.3 \text{ W h kg}^{-1}$  with the same power density of  $\sim 250 \text{ W kg}^{-1}$ , respectively, which are far higher than the value of commercial activated carbon based supercapacitors,<sup>56</sup> and it can be comparable with some reported biomass activated materials<sup>24,26,31,35,45,57</sup> and activated carbon<sup>56</sup> (listed in Table S3†). Moreover, even at a high power density of  $5000 \text{ W kg}^{-1}$   $\text{FAC}_2$  and  $\text{HAC}_2$  still retain  $5.7 \text{ W h kg}^{-1}$  and  $6.2 \text{ W h kg}^{-1}$ , respectively, indicating excellent rate performance of the two electrodes.

Electrochemical impedance spectroscopy (EIS) is widely used to investigate the ion transport effect between electrolyte and electrode interface. The Nyquist plots of  $\text{FAC}_x$  and  $\text{HAC}_x$  are showed in Fig. 9a and b. The equivalent electrolyte ions transfer internal resistances at the electrode interface of  $\text{FAC}_1$ ,  $\text{FAC}_2$  and  $\text{FAC}_3$  are almost  $1.86 \Omega$ ,  $0.94 \Omega$  and  $1.12 \Omega$  in high frequency region, respectively, and the line of  $\text{FAC}_2$  displays the straightest among that of  $\text{FAC}_x$  in the low frequency region, which indicates that  $\text{FAC}_2$  electrode presents lower ion diffusion resistance and better capacitance behavior.<sup>58</sup> In contrast, the equivalent series resistances of  $\text{HAC}_1$ ,  $\text{HAC}_2$  and  $\text{HAC}_3$  are  $1.98 \Omega$ ,  $0.62 \Omega$  and  $0.90 \Omega$ , respectively, and  $\text{HAC}_2$  electrode shows the

Table 1 Specific capacitance and rate performance of  $\text{FAC}_x$  and  $\text{HAC}_x$  electrodes at different current densities

Sample	$1.0 \text{ A g}^{-1}$	$2.0 \text{ A g}^{-1}$	$5.0 \text{ A g}^{-1}$	$10.0 \text{ A g}^{-1}$	$20.0 \text{ A g}^{-1}$	Capacitance retention
$\text{FAC}_1$	$191.8 \text{ F g}^{-1}$	$165.6 \text{ F g}^{-1}$	$116.0 \text{ F g}^{-1}$	$105.0 \text{ F g}^{-1}$	$84.0 \text{ F g}^{-1}$	43.7%
$\text{FAC}_2$	$209.3 \text{ F g}^{-1}$	$204.6 \text{ F g}^{-1}$	$194.5 \text{ F g}^{-1}$	$186.0 \text{ F g}^{-1}$	$176.0 \text{ F g}^{-1}$	84.1%
$\text{FAC}_3$	$201.8 \text{ F g}^{-1}$	$197.6 \text{ F g}^{-1}$	$191.0 \text{ F g}^{-1}$	$184.0 \text{ F g}^{-1}$	$163.0 \text{ F g}^{-1}$	80.8%
$\text{HAC}_1$	$158.3 \text{ F g}^{-1}$	$145.4 \text{ F g}^{-1}$	$122.0 \text{ F g}^{-1}$	$105.0 \text{ F g}^{-1}$	$73.0 \text{ F g}^{-1}$	46.1%
$\text{HAC}_2$	$238.6 \text{ F g}^{-1}$	$230.6 \text{ F g}^{-1}$	$218.0 \text{ F g}^{-1}$	$206.0 \text{ F g}^{-1}$	$179.0 \text{ F g}^{-1}$	75.0%
$\text{HAC}_3$	$207.2 \text{ F g}^{-1}$	$198.8 \text{ F g}^{-1}$	$184.0 \text{ F g}^{-1}$	$162.0 \text{ F g}^{-1}$	$128.0 \text{ F g}^{-1}$	61.8%



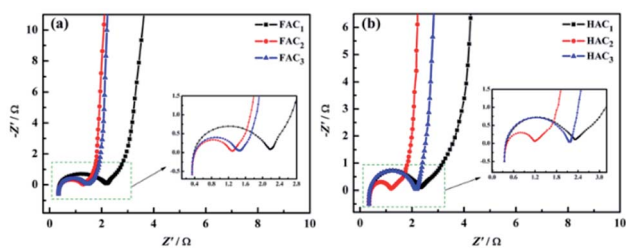


Fig. 9 Electrochemical impedance spectroscopy of (a)  $\text{FAC}_x$  and (b)  $\text{HAC}_x$  electrodes.

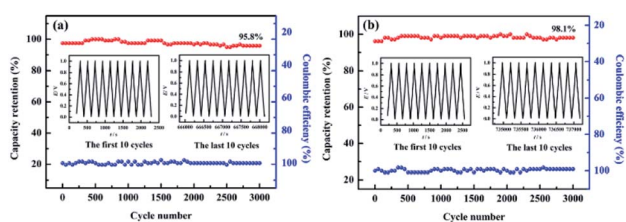


Fig. 10 Cycling stability and coulombic efficiency of (a)  $\text{FAC}_2$  and (b)  $\text{HAC}_2$  electrodes at  $1.0 \text{ A g}^{-1}$  for 3000 cycles. Inset: the GCD curves of the first and last ten cycles.

straightest line with a nearly  $90^\circ$  angle in the low frequency region, suggesting that it can efficiently reduce ions transfer resistance at the stage of charge–discharge and demonstrating ideal capacitance behavior. In essence, rich micro-mesoporous structure and high specific surface area of carbon materials can provide more efficient channels for electrolyte ions, which can shorten ion transport path, and greatly reduce charge transfer resistance and improve the utilization ratio of electrode active materials, and then improve the electrochemical performance.

The cycling lifetime for  $\text{FAC}_2$  and  $\text{HAC}_2$  materials were also investigated at the current density of  $1.0 \text{ A g}^{-1}$  in  $6.0 \text{ M KOH}$ . As shown in Fig. 10,  $\text{FAC}_2$  and  $\text{HAC}_2$  represent no apparent capacity shrinkage after 3000 cycles, and maintain 95.8% and 98.1% of the initial discharging capacity, respectively. Coulomb efficiency is also a mean of evaluating the electrochemical performance of supercapacitors, which is calculated by the ratio of discharge capacity to charge capacity during the same cycling process. The coulombic efficiency curves are showed in Fig. 10. It is apparent that the coulombic efficiency of  $\text{FAC}_2$  (shown in Fig. 10a) and  $\text{HAC}_2$  (shown in Fig. 10b) electrodes are around 100%, which indicate good reversible behavior and no any side reactions taking place during GCD cycling test.<sup>59</sup> In a word, the two electrode materials both present excellent cycling stability and outstanding charge–discharge efficiency.

## Conclusions

$\text{FAC}_x$  materials were prepared from black fungus and  $\text{HAC}_x$  materials were produced from *Hericium erinaceus* via KOH chemical activation. Different activation temperature has great effect on the pore structure and pore diameter of prepared carbon materials, and then influences their electrochemical

performance. The O, N-codoped  $\text{FAC}_2$  and  $\text{HAC}_2$  materials present unique hierarchical porous structure and satisfied surface area. Meanwhile  $\text{FAC}_x$  and  $\text{HAC}_x$  as electrode materials for supercapacitor exhibit an outstanding electrochemical performance, for instance, the satisfied specific capacitance of  $\text{FAC}_2$  ( $209.3 \text{ F g}^{-1}$ ) and  $\text{HAC}_2$  ( $238.6 \text{ F g}^{-1}$ ) at  $1.0 \text{ A g}^{-1}$ , excellent rate performance (the capacitance retention at  $20 \text{ A g}^{-1}$  of  $\text{FAC}_2$  and  $\text{HAC}_2$  are 84.1% and 75.0%, respectively) and prominent cycling performance ( $\text{FAC}_2$  and  $\text{HAC}_2$  almost no apparent capacity loss after 3000 cycles). And the corresponding maximum energy densities of  $\text{FAC}_2$  and  $\text{HAC}_2$  reach at  $7.3 \text{ W h kg}^{-1}$  and  $8.3 \text{ W h kg}^{-1}$ , respectively. These results imply that the oxygen-rich hierarchical porous carbon ( $\text{HAC}_2$ ) shows higher specific capacitance and energy density and longer cycling performance. Nevertheless, carbon-rich hierarchical porous carbon ( $\text{FAC}_2$ ) demonstrates excellent rate performance. The two biomass-derived porous and O, N-codoped activated carbons are potential electrode materials for supercapacitors.

## Author contributions

Xinxian Zhong: data curation, formal analysis, writing original draft, funding acquisition. Quanyuan Mao: resources, formal analysis, visualization. Zesheng Li: formal analysis, visualization. Zhigao Wu: data curation, formal analysis. Yatao Xie: visualization. Shu-Hui Li: supervision, writing – review & editing. Guichao Liang: data curation, formal analysis. Hongqiang Wang: supervision, writing – review & editing, funding acquisition.

## Conflicts of interest

There are no conflicts to declare.

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