Cicada slough-derived heteroatom incorporated porous carbon for supercapacitor: Ultra-high gravimetric capacitance

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A B S T R A C T

Heteroatom incorporated porous carbon from cicada slough, has been synthesized through a simple activation process. The cicada slough-based porous carbon has high potency of naturally-derived heteroatom functionalities (~12.06% atomic ratio of nitrogen, oxygen, sulfur, and phosphorus), well-developed microporosity and high specific surface area (1676 m² g⁻¹). Supercapacitor involves the as-obtained carbon as electrode material showing ultra-high specific capacitance of 353 F g⁻¹ at the current density of 1 A g⁻¹ and excellent rate capability of 284 F g⁻¹ at 30 A g⁻¹. The retention of specific capacitance of the working electrode remains over 90% after 3000 cycles at 10 A g⁻¹. Single electrode in the symmetric-two-electrode test also delivers high specific capacitance of 274 F g⁻¹ with the energy density up to ~9.0 Wh kg⁻¹ in aqueous electrolyte. These outstanding results suggest the biomass derived porous carbon possessing the potential for the fabrication of high performance supercapacitors.

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1. Introduction

As a new type of advanced energy storage device, electrochemical capacitors (ECs) has attracted extensive attention recently due to excellent power density, long cycle life, fast charge-discharge rate and wide operating temperature range. Based on mechanisms of energy storage, supercapacitors can be classified as electrical double-layer capacitors (EDLCs) and pseudo-capacitors. Specifically, the capacitance of EDLCs is arisen from the pure electrostatic attraction between ions/molecules of electrolyte and the charged surface of carbon-based electrode materials, while capacitance of pseudo-capacitors is associated with fast reversible Faradaic redox reaction of electro-active species at the interface between electrolyte and electrode materials [1]. Although ECs possesses higher power density and longer cycling stability, they suffer from an order of magnitude lower energy density (E) relative to batteries, especially as far as EDLCs [2]. According to the quantitative calculation equation $E = 0.5CV^2$, when the operation voltage ($V$) is kept constant, $E$ is positively correlated with capacitance ($C$). Hence, to develop efficient synthesis processes and/or design of novel and well-constructed materials with high-performance capacitance are regarded as effective approaches to improve the energy density.

Over the past decade, porous carbon materials including activated carbons [3–11], templated carbons [12,13], carbon nanotubes [14,15], carbide-derived carbons [16,17], carbon fibers [18,19], carbon aerogels [19,20] and graphene [2,21] have been extensively investigated as electrode materials for EDLCs. Among various carbon materials, the ACs has been considered to be one of the most convincing materials. On one hand, the ACs possesses high SSA (e.g. > 2000 m² g⁻¹) and well-balanced pore size distribution (PSD), which are key factors to enhance the specific capacitance and to improve the rate capability [7–9]. On the other hand, abundant and sustainable resources, simple and easy processes, and high yield suggest that they are more suitable for the industrial production and commercial applications [22,23]. In addition, heteroatom functionalities (e.g. N, P, and S) are often incorporated in ACs, particularly when using natural biomass as precursors [3,18,24–26]. These functionalities can enhance the materials’
conductivity and wettability as well as provide extra faradaic pseudo-capacitance. Studies have shown that the N atoms can enhance the pseudo-capacitive effect and improve the electronic conductivity of carbon materials \[3,10\]. The P-doping is understood to stabilize oxygen functionalities during electrochemical charging, improving the reaction stability \[26\]. For the S-containing carbon, the introduction of n-type dopant, i.e., sulfur atoms, not only afford more polarized surface but also provides reversible pseudo-sites and thus brings about superior capacitive capacity \[27\]. More recently, researchers have already utilized various renewable biomasses or organic wastes, such as foods, agricultural and daily-life wastes, marine products, microorganism and even animal tissues for the meticulous synthesis of manifold ACs \[3,11,22,26\]. Those carbons exhibited appealing electrochemical capacitive storage capacity. Biomass has been perceived as one of the most competitive candidates for providing high-quality carbon electrode materials \[3,11,22,26\].

Chitin ((CH\(_2\IH\(_2\)NO\(_5\))\(_n\)), a polysaccharide composed of glucosamine and N-acetylglucosamine, which is a structural component generally found in cell walls of fungi, exoskeletons of insects and other arthropods such as crustaceans (e.g., lobsters, shrimps and crabs) \[28\]. Only to cellulose, chitin is the second most abundant biopolymer in the flora and fauna in the nature. Estimation shows that chitin is biosynthesized in an amount of \(10^{10} - 10^{11}\) tons per annum \[29\]. Serving as a sort of carbon and nitrogen precursor, carbon materials based on chitin and its derivatives, e.g. chitosan, have been successfully synthesized and employed as electrode materials for ECs \[30,31\].

It is intriguing that cicada slough (CS) contains plentiful chitin \[28\]. CS, officially named Periostracum Cicadae, is a translucent and luster shell, which can be obtained after the elision of the larvae of periodical cicadas (Hemiptera: Cicadidae Periostracum Cicadae Fabricius). Cicadas abound in the area from temperate to tropical climates. They can be found on all continents except Antarctica and its reproduction is highly efficient. In Henry S. Dybas’ study in Raccoon Grove (U.S.), the mean density of periodical cicadas was estimated up to 3114 ± 41.30 and 27.4 ± 3.03 nymphs per square yard, or about 1,500,000 and 133,000 nymphs per acre in the forest plain and upland areas, respectively \[32\]. Other studies also showed that periodical cicadas were the most abundant herbivores in North American deciduous forests in both number and biomass \[28\]. Besides chitin as the main component, CS also contains proteins, amino acids, which also can be considered as effective nitrogen sources as well. Other nonmetallic heteroatoms such as sulfur and phosphorous were also determined in the matrix of CS \[28,34\].

We herein first utilized CS as a precursor, employing two simple and convenient steps of carbonization and activation process to synthesize heteroatom incorporated porous carbon. With the help of potassium hydroxide, the as-obtained carbon exhibited high SSA, well-developed microporosity, and high potency of heteroatom functionalities. ECs electrode contained the carbon sample harvested a superior performance with SCs of 355 and 288 F g\(^{-1}\) in 6.0 M KOH electrolyte at current densities of 1.0 and 10 A g\(^{-1}\), respectively. Thus, this CS-based porous carbon possessed the potential for application as ECs electrodes with high energy and power density.

2. Experimental section

2.1. Materials synthesis

Cicada slough was obtained from Jinling Pharmaceutical, Nanjing. All reagents were used as-received without further purification. Deionized water was used throughout the experiments. Washed, powdered and dried cicada slough was preliminary pre-carbonized at 600 °C for 60 min under N\(_2\) atmosphere with a heating rate of 4 °C min\(^{-1}\). The obtained residue was then thoroughly washed with 0.5 M HCl and deionized water until neutral pH. Dried at 70 °C and the CCS-600 sample was obtained. The sample was mixed with KOH (weight \(\text{KOH}/\text{weight Carbon} = 3\)) and was pyrolyzed at 650 °C for 60 min under protective gas with a heating rate of 4 °C min\(^{-1}\). The resulting dark solid body was washed with 0.5 M HCl, deionized water and ethanol in turn. The resultant activated carbon was denoted as PCCS-600-650 (abbreviated as PCCS).

2.2. Characterizations

Thermal gravimetric analysis and differential scanning calorimetry were conducted on a PerkinElmer Pyris 1 DSC instrument, the heating rate was 10 °C min\(^{-1}\) from 30 to 700 °C with N\(_2\) carrier gas. The surface functional groups were investigated by Fourier transforms infrared spectra (Varian Excalibur 3100). The powder X-ray diffraction data from 5° to 80° was measured on a Thermo ARL XTRA instrument with Cu-Kz radiation generated at 40 kV. The microscopic morphology and structure were observed by FEI Nova NanoSEM 450 scanning electron microscope working at 15 kV and FEI Tecnai G2 20 transmission electron microscope measurements operating at 200 kV. The Raman spectrum was carried out on Renishaw in Via 2000 Raman spectrometer with Ar laser wavelength of 458 nm. X-ray photoelectron spectroscopy analysis was taken on a Thermos Scientific K-Alpha spectrometer with Al Kz (1486.6 eV) as the X-ray source, and all of the data acquisition and processing were fitted with XPS PEAK41 software. N\(_2\) adsorption/desorption isotherm was measured at 77 K employing a Tristar II 3020 surface area analyzer (Micromeritictics, USA), Brunauer-Emmett-Teller model was performed to measure the specific surface area. The pore size distribution was analyzed based on Horvath-Kawazoe and Barrett-Joyner-Halenda models for micropore and mesopore, respectively.

2.3. Electrode fabrication and electrochemical measurements

All electrochemical characterizations were carried out on a CHI660D electrochemical workstaton (Shanghai Chenhua Inst.) in 6.0 M KOH aqueous electrolyte. For the preparation of working electrodes, a viscous slurry containing 85 wt% PCCS, 10 wt% acetylene black and 5 wt% polytetrafluoroethylene was intensive mixed and pressed onto a nickel foam current collector. The as-formed electrode was then dried at 100 °C in a vacuum oven. The loading mass of active substance was ~3 mg. For three-electrode test, the current collector, a platinum plate and a saturated calomel electrode were used as the working, counter and reference electrodes, respectively. Cyclic voltammetry curves were obtained in the potential window range from −1.0 to −0.1 V by varying the scan rate from 5 to 100 mV s\(^{-1}\). Galvanostatic charge-discharge at current densities from 0.5 to 30 A g\(^{-1}\). Electrochemical impedance spectroscopy was measured in a frequency range of 0.01 Hz−10 kHz at open circuit voltage with alternate current amplitude of 5 mV. For two-electrode system test, the preparation of two working electrodes according to the procedure described above and they were symmetrically assembled with a non-woven fabric as separator. To facilitate the quantitative evaluation of the test data, the specific capacitance (\(C_p\), F g\(^{-1}\)) is calculated from the galvanostatic charge-discharge values by using the following equation:

\[
C_p = \frac{It}{m \Delta V} \quad \text{(for 3–electrode test)}
\]

and...
The energy density \( E \) (W h kg\(^{-1}\)) and power density \( P \) (W kg\(^{-1}\)) of symmetrical electrode tests are calculated according to:

\[
E = \frac{1}{2} \times \frac{C_p}{m} \Delta V^2 \frac{1}{3\Delta t}
\]

and

\[
P = \frac{E \times 3600}{\Delta t}
\]

where \( C_p \) (F g\(^{-1}\)) represents the capacitance and \( \Delta t \) (s) is the discharge time referring to the voltage interval (not including the IR drop) of the above two-symmetric-electrode test. The divisor 4 is discharge time referring to the voltage interval (not including the IR potential window excluding the IR drop (V) within the discharge time.

### 3. Results and discussions

Scheme 1 showed the typical schematic flow diagram. For characterization, activated carbon resulted from CS was represented as PCCS and the non-activated carbon was corresponded named CCS. The thermogravimetric analysis (TGA), derivative TGA (DTG), and differential scanning calorimetry (DSC) were used to monitor the thermolysis process (Figure S1, ESI). At initial moderate temperature (30–270°C), CS starts to degrade and produces volatiles. Then, CS substantially decomposes between 270°C and 430°C (DTG curve) with a weight-loss from ~91% to ~52% (TG curve). A prominent exothermic peak has been observed around ~380°C (DSC curve), suggesting that the precursor is being rapidly decomposed while releasing substantive heat. During the latter temperature range, thermal decomposition dynamics of chitin could be described as a set of concurrent and consecutive reactions for the decacylation and pyrolysis of polysaccharide’s main chain [34,35]. Coupled with chitin, other organic ingredients such as proteins would also be carbonized during that range [36].

The FT-IR was used to identify the surface functional groups of PCCS. As shown in Fig. 3a, peaks located at 3455–3488 cm\(^{-1}\) have been attributed to the hydroxyl group (OH) and/or chemisorbed water on the surface of sample. The small sharp peak at ~1632 cm\(^{-1}\) has been likely to the absorption signal of the vibration of carbonyl group (C=O) and/or stretching vibration of C=C in aromatic ring. The relatively broad signal centered at ~1081 cm\(^{-1}\) should be assigned to the C-O or C-N stretching vibration [37].

XPS was then employed to reinforce the qualitative and quantitative analysis of surface chemical composition for PCCS. The XPS spectrum in Fig. 1a has confirmed the multiple co-existences of C, N, O, P and S elements. Fittings of the spectrum to each element suggests that PCCS mainly contained carbon (~87.94 at%) along with small quantities of oxygen (~8.94 at%), nitrogen (~2.72 at%), trace amount of phosphorus (~0.27 at%) and sulfur (~0.13 at%) elements (Table 1). The heteroatom (N, S and P) should be originated from the precursor itself [27,34]. After chemical activation process, the content of heteroaotm in PCCS (~12.06 at% total content of N, O, P, and S) is decreased in comparison with CCS (~16.98 at%). The high-resolution (HR) C 1s spectrum (Fig. 1b) can be resolved into four individual peaks centered at 284.5, 285.1, 286.2 and 288.4 eV, which refers to C-C, C-N, C-O and C=O/C=O, respectively [38]. Five individual peaks corresponding to pyrrolic N (~398.3 eV, ~398.6 at%), nitrile/amine N (~399.7 eV, ~16.7 at%), pyrrolic N (~400.3 eV, ~18.4 at%), graphitic N (~401.3 eV, ~11.0 at%), and oxidized N (402.1–403.0 eV, ~16.2 at%) can be extracted from the HR N 1s signals (Fig. 1c). Here, different N species were calculated by using the Gaussian fitting method [3,10,11]. Studies have shown that the pseudo-capacitive is triggered on negatively charged pyridinic N and pyrrolic N. Meanwhile, the positively charged graphitic N and oxidized N help the electron transfer, which is beneficial for improving the electronic conductivity of carbon materials [3,10]. HR O 1s spectrum presented in Fig. 1d revealed the existence of several types of oxygen-based groups including the adsorbed oxygen (~531.1 eV), C=O/C=O (~532.3 eV) and O=C-O (~533.1 eV), and N-O (~534.3 eV) functional groups were also detected [11]. The deconvolution of HR P 2p core-level peaks reveals the presence of two contributions at binding energies of ~131.2 and 133.1–133.8 eV with the distributions of C-P-C bond and oxidation state of phosphorus, respectively (Fig. 1e) [25]. The HR S 2p can be extracted with three peaks (Fig. 1f). Specifically, owing to the spin-orbit couplings, -C=S-C- covalent bond of the thiophene-S is grouped into S 2p3/2 (164.1 eV) and S 2p1/2 (165.3 eV), respectively. The intensive peak, centered at 168.6 eV should be contributed by oxidized sulfur, such as sulfonate (-C-SO\(_3\)-C-) or sulfate (-C-SO\(_4\)-C-) [39].

SEM images (Fig. 2a) have revealed that PCCS has a 3D morphology, which is composed of irregular sheets or blocky textures. Fig. 2b clearly demonstrates the porous characteristics of the texture. SEM images of finely ground CCS have been shown in Figure S2 (ESI). As a result of activation, much less porous carbon blocks (for CCS) have been etched by KOH in high temperature through oxidizing part of carbon into carbonate and oxycarbide, and thus the pores are created (for PCCS). Further structural information has been examined through TEM, as shown in Fig. 2c and d. The irregular, blocky texture with dispersive micro-pores and channels at nanoscale and sub-nanometer range are observed. No visible lattice fringe (Fig. 2d inset) is found in the HRTEM, implying the amorphous feature of the carbon wall.

XRD and Raman spectroscopy were invested to further confirm the microstructure analyzed by HRTEM. In XRD pattern (Fig. 3b), characteristic peaks around 2θ = 26.5° and 43.7° are corresponded to the (002) and (101) planes, respectively, which matches the diffraction planes of the hexagonal graphite. The fact that (002) diffraction peak is weak in intensity, indicating the low graphitized
Fig. 1. (a) XPS spectrum of PCCS, (b–f) high-resolution XPS analyses of C 1s, N 1s, O 1s, S 2p and P 2p. (A colour version of this figure can be viewed online.)
carbon structure [9]. The high intensity diffraction peak in the low-angle scattering is in agreement with the high density of micropores [2,8]. Raman spectrum in Fig. 3c showed both D-band (corresponded to the disorder-induced features) and G-band (representative the graphite in-plane stretching vibrations) peaks have been respectively absorbed located at ~1340 cm\(^{-1}\) and ~1590 cm\(^{-1}\). That relative intensity ratio \(I_D/I_G\) ~1.14 indicates the low degree of crystallization [3]. Analysis results based on XRD pattern and Raman spectrum is in agreement with the structural characteristics observed by HRTEM.

For a more detailed analysis of the microstructure, the SSA and PSD were determined by the N\(_2\) adsorption-desorption measurement. According to the IUPAC classification, the curve of PCCS exhibits a typical type-I sorption isotherm with the steep uptake below \(P/P_0 = 0.02\) and approaches to the saturated adsorption at a relative pressure \((P/P_0)\) of ~0.2 (Fig. 3d), which suggests the existence of more micropores than mesopores. The SSA \((S_{BET})\) of PCCS has been calculated as high as 1676 m\(^2\) g\(^{-1}\) with total pore volume \((V_{total})\) of ~0.94 cm\(^3\) g\(^{-1}\) determined at \(P/P_0 = 0.99\), the Langmuir SSA has been calculated up to ~2563 m\(^2\) g\(^{-1}\). It has been mentioned that ~70.5% of the SSA is contributed by micropores according to the \(t\)-plot calculations. The PSD plots shown in Fig. 3e and f clearly further confirmed the presence of abundant micropores (<2 nm), and small proportion of narrow mesopores (2–5 nm). The activation process effectively creates abundant pores in CCS, resulting in the enlargement of \(S_{BET}\) markedly from 9.8 to 1676 m\(^2\) g\(^{-1}\) and the improvement of \(V_{total}\) from 0.0050 to 0.94 cm\(^3\) g\(^{-1}\) (Table S1).

On the basis of the analysis of XPS spectra, N\(_2\) sorption measurement isotherms and SEM recorded images, it can be confirmed that the PCCS sample not only possesses high potency of heteroatom functionalities but is endowed with large SSA and well-developed porosity, ranging from the micro- to macro-scale, especially a large volume of micropores. Generally, mesopores and macropores provide smooth and convenient rapid ion-transfer pathways and buffered ion-storage sites, and meanwhile, micropores have offered sufficient space for ion/charge storage [38]. The in-situ incorporated N-doping enhances the pseudo-capacitive effect and has improved the electronic conductivity of carbon materials [3,10,25]. The P-atoms benefit the reaction stability by means of stabilizing oxygen functionalities during the electrochemical charging [26]. For S-doping, a more polarized surface and reversible pseudo-sites are provided, contributing to the superior performance [27].

The electrochemical performance of carbon electrodes were examined using cyclic voltammogram (CV), galvanostatic charge/discharge (GCD) and electrochemical impedance spectroscopy (EIS) in 6.0 M KOH aqueous electrolyte. The quasi-rectangular CV curves (Fig. 4a) indicates typical characteristics of ACs-based EDLCs but part contribution of pseudo-capacitance can be seen, which may be induced by the reversible faradaic redox reaction of heteroatom functionalities. The IR drop at the start of discharge process is related to the equivalent series resistance (ESR, Ohm) phenomenon, which can determine the effective maximum voltage of the device during discharge and therefore limit the maximum energy and power density of EDLCs [40,41]. Approximate isosceles triangle shapes GCD curves at diverse current densities (Fig. 4b) with small IR drops (0.0083 V and 0.0629 V at 0.5 Ag\(^{-1}\) and 5 Ag\(^{-1}\), respectively) indicate the low ESR.

After the activation, the high density of hierarchically porous structure is capable of accommodating the storage and fast...
transport of more ions. The structures remarkably improve the energy storage capacity. As presented in Fig. 4b and c, the PCCS electrode exhibits preeminent SCs of 355, 328, 312 and 297 F g\(^{-1}\) at current densities of 1, 2, 4 and 8 A g\(^{-1}\), respectively. These SCs values are higher than the vast majority of bio-derived carbon materials of typical reports under similar test conditions in recent years (Table S2, ESI\(^{y}\)). Even at a current loading of 30 A g\(^{-1}\), the SC is still as high as 284 F g\(^{-1}\) (80% of 355 F g\(^{-1}\)), revealing the superior rate capability. Comparatively, CCS without any process except one step of carbonization only shows SCs of 31 F g\(^{-1}\) and 19 F g\(^{-1}\) at current densities of 0.5 A g\(^{-1}\) and 5 A g\(^{-1}\), respectively (Figure S3, ESI\(^{y}\)). It is noteworthy that the surface area normalized capacitance of PCCS based on \(S_{\text{BET}}\) is calculated as 25.1 mF cm\(^{-2}\) at the current density at 0.5 A g\(^{-1}\) (Figure S4, ESI\(^{y}\)), which has reached the upper limit of theoretical capacitance (10–25 μF cm\(^{-2}\)) of EDLCs [6].

Electronic conductivity is also an important factor which affects the energy storage performance. The Nyquist plot (Fig. 4d) originated from the EIS in a frequency range from 0.01 Hz to 10 kHz exhibits representative characters of EDLCs. A distinct semi-circle segment shows the characteristics of the bulk electrolyte resistance (\(R_s\)) and charge transfer resistance (\(R_{ct}\)). A short 45° slope of Warburg segment at medium frequencies indicates the fast diffusion/transport of ions on the electrode surface or within the bulk of carbon electrode walls in the electrolyte. A nearly vertical line reflects almost ideal capacitive behavior at low frequencies [26,31]. The top panel in Fig. 4d shows the Randles equivalent electrical circuit based on the fitting of EIS data. Where \(C_{dl}\) is the double-layer capacitance linked to a charge accumulation at the electrode/electrolyte interface, \(W\) is referred to the diffusion/transport (or Warburg) impedance. The impedance is intended to define the polarization of an electrochemical system due to diffusion limitation. While \(R_s\) (0.97 Ohm) and \(R_{ct}\) (0.87 Ohm) can be quantified from the semi-circle segment that left intersection with the horizontal real axis (Z') and the right intercept of the same segment,

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**Table 1**

Chemical composition of PCCS and CCS samples determined by XPS (atom %).

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCCS</td>
<td>87.94</td>
<td>2.72</td>
<td>8.94</td>
<td>0.27</td>
<td>0.13</td>
</tr>
<tr>
<td>CCS</td>
<td>83.02</td>
<td>5.01</td>
<td>11.21</td>
<td>0.50</td>
<td>0.27</td>
</tr>
</tbody>
</table>

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Fig. 3. (a) FT-IR spectrum, (b) XRD pattern, (c) Raman spectrum, (d) Nitrogen adsorption/desorption isotherm, and (e, f) microporous and mesoporous size distributions based on the Horvath-Kawazoe and Barrett-Joyner-Halenda model, respectively.
respectively (Fig. 4d bottom inset) [40]. A nearly $-90^\circ$ phase angle in the Bode plot as shown in Fig. 4e, which has confirmed the ideal capacitive behavior at the low-frequency region. The characteristic frequency $f_0$ at $-45^\circ$ phase angle is $0.97$ Hz, which corresponds to the time constant $\tau_0 (=1/f_0)$ of $1.03$ s. A much shorter time constant means that the faster ion/charge transport rate is faster [26,41]. The retention of SC of the working electrode remained over 90% after 3000 cycles at $10$ A g$^{-1}$ (Fig. 4f) suggests an excellent cycling stability.

Two-symmetric-electrode electrochemical tests were also evaluated to estimate the electrochemical performance of PCCS. As profiled in Fig. 5b, single electrode still delivers high SCs of $274$ F g$^{-1}$ and $232$ F g$^{-1}$ at current densities of $1$ A g$^{-1}$ and $4$ A g$^{-1}$ in $6.0$ M KOH electrolyte, respectively, and the SC has remained as high as $182$ F g$^{-1}$ under the current density of $20$ A g$^{-1}$ (Fig. 5c). Fig. 5d showed Ragone plot of PCCS corresponding to the relationship of energy densities and power densities. Electrodes have delivered a maximum energy density ($E$) of $9.0$ W h kg$^{-1}$ with the power density of $227$ W kg$^{-1}$ at a $1$ A g$^{-1}$ current loading, which is not only higher than commercial activated carbon based electrode materials (typically $E$ with the order of $4$–$6$ W h kg$^{-1}$) [2], but higher than previously reported bio-carbon-based symmetric ECs with similar test conditions (detailed scatters inserted in Fig. 5d) [5,20,26,37,41–44].

4. Conclusions

In summary, with the help of activation process, the activated carbon product (PCCS) from cicada slough has a high SSA, well-developed PSD and rich heteroatom functional groups. The porous material not only provides enough attachment sites for ions and shortened the transport distance, but also brings the non-ignorable pseudo-capacitance effects. Thus, the carbon electrode shows an enhanced specific capacitance of $355$ F g$^{-1}$ at a current density of $1$ A g$^{-1}$ and an excellent rate capability of $284$ F g$^{-1}$ at $30$ A g$^{-1}$. In Symmetric electrodes test, the carbon electrode also performs superior properties of $274$ F g$^{-1}$ specific capacitance and an energy density up to $9.0$ W h kg$^{-1}$. In the sense of the abundance of CS, the facile and convenient process, and the excellent capacitive storage and superior rate capability, PCCS is highly hopeful as electrode material for high performance supercapacitors.
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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.carbon.2018.11.011.

References


