Novel electrode material derived from porous polymeric organic framework of phloroglucinol and terephthaldehyde for symmetric supercapacitors

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ABSTRACT

In this paper, we report a novel pore enriched carbon derived from polymeric organic framework (POF) of phloroglucinol and terephthaldehyde by solvothermal method followed by pyrolysis under an inert atmosphere at 800 °C (POF-800) for symmetric supercapacitor (SSC) applications. The as-prepared POF and POF-800 were characterized by the following techniques. To identify the functional groups, Fourier transform infrared spectroscopy (FT-IR) was used. The surface morphology was analyzed through scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Thermal stability and the oxidation state of the element was studied by thermogravimetric analysis (TGA) and x-ray photoelectron spectroscopy (XPS), respectively. POF-800 electrode shows a maximum surface area of 352 m² g⁻¹. In a three-electrode system, POF-800 electrode showed 50.1 F g⁻¹ of specific capacitance at 0.25 A g⁻¹ current density. Also, the SSC electrode exhibited specific capacitance of 46.3 F g⁻¹ at 0.5 A g⁻¹ with exceptional long term stability (5000 cycles) and moderate energy density of 14.48 Wh kg⁻¹ in 6 M KOH electrolyte. The present finding opens a new avenue for well-developed porous carbon materials to encourage advanced supercapacitor device for superior electrochemical energy storage.

1. Introduction

In this present decade, supercapacitors (SCs) have been attracted substantial attention and considered to be one of the significant energy storage and power harvest machinery for electric vehicles, renewable energy systems and portable electronic devices [1,2]. SCs accumulate energy by one of the following two ways, (i) electric double layer capacitance (EDLC, ion absorption) or (ii) pseudocapacitance (PC, by fast surface redox reactions). EDLC works by the electrostatic accretion of charge from the reversible adsorption and desorption of ions and arrangement of polar solvent molecules between the supporting electrolyte and the surface of the electrode. Thus, the total amount of charge stowed is directly proportional to the capacitance of the electrode material [3] and henceforth the materials possess high surface area (m² g⁻¹) are more beneficial, however a direct linear relationship from capacitance to surface area is not always found [4]. The SCs performance sturdily depends on the active electrode materials selection. To date, a variety of materials have been employed in supercapacitor electrodes which include metal oxides [5,6], metal sulfides [7], carbon-based materials [8,9], porous carbon derived from hypercrosslinked polymers (PC–HCP) [10,11] and conducting polymers [12,13]. Among them, PC–HCP has fascinated ample attention from the researchers owing to its excellent properties, such as good surface area, simple synthesis procedure and experimental conditions, massive stockroom of low-cost monomers, excellent thermal and chemical stabilities with robust structure [14].

Wang et al. [15] synthesized high-quality porous carbon nanotubes from 1D hypercross-linked polymer nanotubes by a simple Friedel–Crafts alkylation synthetic route using ferric chloride and formaldehyde dimethyl acetal as the catalyst and cross-linker, respectively for supercapacitor applications. Recently, Lee et al. [16] produced a series of heteroatom incorporated carbon materials from hypercross-linked polymers of benzene, pyrrole, thiophene, and aniline for supercapacitor applications. Very recently, Suresh Babu et al. [11]synthesized a novel
porous carbon nanofiber derived from a facile Friedel–Crafts alkylation reaction with naphthalene and α, α’-dichloro-p-xylene for asymmetric supercapacitor applications. However, Friedel–Crafts reactions are generally catalyzed by heavy and/or transition-metal catalysts which have some disadvantages like high cost and pollute the environment [17]. Moreover, most of the reagents used the aforesaid HCPs are produced via multiple steps. Novel reactions using low-priced and inexpensive raw materials with non-noble metal catalysts, even without catalysts might show profound benefits for the construction of porous polymeric organic framework (POF).

Herein we designate a novel method to persuading microporosity involving phenolic resin-inspired or Bakelite-type chemistry. Phenolic resins contain a huge family of polymers which are added by the condensation reactions of phenol with formaldehyde, with Bakelite (polyoxybenzylmethylenglycolanhydride) being one of the first members of this family. Phenolic molecules have many active moieties and hence it’s appropriate for electrophilic aromatic substitution. They are connected through the formaldehyde carbon followed by the elimination of a water molecule (H₂O). These condensation reactions began with the heating in the presence of catalyst either by acids (hydrochloric acid/zinc chloride) or bases (ammonia). It purely depends on the ratio of phenol to formaldehyde [18]. Thanks to Katsoulidis and Kanatzidis [19] who synthesized a solvothermal cross-linking of phloroglucinol with terephthaldehyde in the absence of catalyst for CO₂ adsorption and not for supercapacitor applications. This above-mentioned chemistry/principle inspired us to explore the electrochemical activity of new pores enriched material bearing reactive organic groups (polyphenolic resin) at its surface.

To the best of author’s knowledge, phloroglucinol and terephthaldehyde based POF have not been previously reported for supercapacitor applications. Here we describe the preparation of a novel POF derived from phloroglucinol and terephthaldehyde. The obtained POF in good yield without any catalyst. The POF-800 (pyrolyzed POF) showed good surface area up to 352 m² g⁻¹ and exhibit maximum specific capacitance of 46.3 F g⁻¹ at 0.5 A g⁻¹ current density in a two-electrode system (symmetric supercapacitor). POF-800 electrodes exhibited a wide potential range from 0 to 1.5 V with respect to Ag/AgCl electrode. POF-800 aqueous symmetric supercapacitor demonstrated a wide operating potential +window up to 1.5 V, along with excellent cycling stability after 5000 cycles.

2. Experimental

2.1. Materials

Phloroglucinol (1,3,5-trihydroxy benzene), terephthaldehyde (1,4-benzenedicarboxaldehyde), carbon black, N-methyl-2-pyrrolidone (NMP), polyvinylidene fluoride (PVDF) and nickel (Ni) mesh were procured from Sigma Aldrich, USA. 1,4-dioxane, conc. HCl, 95% ethanol, potassium hydroxide, and acetone were obtained from Daejung Chemicals, South Korea. All the materials were of reagent grade and hence used without additional purification except nickel mesh.

2.2. Synthesis of POF

To synthesize POF, we have been used already reported the procedure by Katsoulidis and Kanatzidis [19] with slight modification. In brief, phloroglucinol (7.93 mmol) and terephthaldehyde (4.62 mmol) in 20 mL of 1,4-dioxane were taken in 30 mL of glass vial closed with an air tightened lid. The resultant solution or mixture was heated solvothermally in a hot-air oven for 10 h at 120 °C. After solvothermal treatment, the brown colored precipitate was centrifuged, and the residue thoroughly cleaned with deionized water and 95% ethanol and dried in an oven for 24 h at 100 °C. The obtained product was a polymeric organic framework derived from phloroglucinol and terephthaldehyde, designated as POF.

2.3. Pyrolysis of POF

The synthesized POF was annealed at 800 °C under inert atmosphere (argon gas) for 5 h with the heating rate of 2 °C min⁻¹ and named as POF-800.

2.4. Physicochemical characterization

The superficial morphology of the POF and POF-800 was probed by scanning electron microscopy (FE-SEM; Hitachi S-2400, Japan) and transmission electron microscopy (TEM; JEOL, Japan). The porous nature and surface area (m² g⁻¹) of the samples were determined from nitrogen sorption isotherm (BET analysis) were measured at −195.8 °C using ASAP 2420 apparatus, Georgia at 77 K. Prior to each adsorption measurement the materials were degassed at 150 °C under vacuum in the de-gas port. The surface area was determined from the linear part of the Brunauer-Emmett-Teller (BET) equation. The identification of the functional groups of POF and POF-800 were studied by Fourier transform infrared spectroscopy (FTIR; JASCO 4000, USA). Raman spectrum was analyzed using high vacuum XperRam 200 (Nano base, Korea) with a 532 nm laser wavelength at ambient conditions. Before the analysis, the samples were pressed on the slide glasses. The oxidation state of the samples was analyzed by XPS technique (VG scientific, ESCALAB 250).

2.5. Electrochemical measurements

Both the three and two electrodes (symmetric device) were used to examine the electrochemical performance of POF-800, and all appropriate experiments were achieved by SP-150 Potentiostat (Bio-Light Science instrument, France). In the three electrode system, Ag/AgCl electrode and platinum wire were served as the reference and counter electrode, respectively. Nickel foam was used as a substrate and it was pretreated with the following procedure. Typically, a piece of nickel foam (1 × 1 cm²) was pretreated with 3 M HCl solution, followed by absolute ethanol and then deionized water in an ultrasonic bath for 10 min to remove the NiO layer and residual organics on the surface of the Ni foam. Then, the retreated nickel foam was dried at 100 °C in an oven for 12 h. The electrode at which the reaction of interest occurs is called working electrode and it was prepared by mixing of 5 wt.% PVDF, 15 wt.% carbon black and 80 wt.% POF-800 (active material) and well ground with the help of mortar and pestle, and then add a few drops of anhydrous NMP solvent slowly until it becomes a thick slurry. Then, the as-prepared slurry was uniformly spread on the pre-treated 1 cm × 1 cm nickel foam and desiccated at 90 °C for 20 h. The weight of each electrode was found to be about 4 mg. Prior to the electrochemical measurement, the fabricated working electrode was pressed at 10 MPa for 1 min. The electrochemical measurements such as cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD) were conducted in the range of potential window from −1.0 to 0 vs. Ag/AgCl with 6 M KOH as the supporting electrolyte. The electrochemical impedance spectroscopy (EIS) was analyzed between the frequency range of 0.01 Hz and 0.1 kHz. As stated by Eq.(1), the specific capacitance (Cₛ) of the prepared POF-800 was evolved from the GCD curve.

\[ C_s = \frac{I}{m \cdot \Delta V} \]  

where \( I \) is the given current (A), \( m \) is the mass of the POF-800 (g), \( \Delta V \) is the range of potential window (E), and \( t \) is the discharge time (s).

In the device (two electrode system), two similar electrodes assembled by using the above- stated protocol. CV and GCD measurements of the cell was done in the potential window from 0 to 1.5 V with respect to Ag/AgCl electrode in 6 M KOH.

The specific capacitance (Cₛ), energy density (Eₑ), and power density (Pₑ) of the symmetric supercapacitor (SSC) were determined with the
below equations [20–22]:

\[ C_d = \frac{2 \times I \Delta t}{m \times \Delta V} \]  
\[ E_d = \frac{1}{2} \times C_0 \times \Delta V^2 \]  
\[ P_d = \frac{E \times 3600}{\Delta t} \]

Here, \( I \) is the current density (A), \( \Delta t \) designates the discharge time (s), \( m \) signifies mass of both the electrodes (g) and \( \Delta V \) represents voltage window (V), respectively. Factor 3.6 was used in Eq. (3) is essential to transform the energy in joules (product of farads × volts) into Wh kg\(^{-1}\).

3. Results and discussion

The FTIR spectra of the starting materials, such as phloroglucinol and terephthaldehyde with polymeric organic framework (POF) were depicted in Fig. S1 (please see supporting information section). Phloroglucinol showed -O-H stretching vibration at 3275 cm\(^{-1}\) and ring vibrations at 1626, 1504, and 1332 cm\(^{-1}\). The peaks at 1154 and 1008 cm\(^{-1}\) are assigned to phenolic –C\(_e\)O- vibrations. The peaks below 1000 cm\(^{-1}\) are assigned to ring C\(_e\)H bending modes. Terephthaldehyde showed peaks due to aldehydic –C\(_e\)H vibration at 2883 cm\(^{-1}\) and C = O vibration at 1685 cm\(^{-1}\). The FT-IR spectra of POF and POF-800 are depicted in Fig. 1(a). The intense peak was observed in the high energy region because of O–H stretching of phenolic OH and alcoholic OH. The peak at 1250 cm\(^{-1}\) again confirms the presence of phenolic OH by its C–O stretching vibration. Also, the presence of alcoholic OH is again confirmed by its C–O stretching at about 1050 cm\(^{-1}\). The brown color of the product and the sharp intense peak at about 1610 cm\(^{-1}\) confirms the initial addition products between phloroglucinol and terephthaldehyde are much dehydrated to extend conjugation between the aromatic rings which leads to forming quinonoid moiety. The peak that appears as a shoulder to the one at 1610 cm\(^{-1}\) in the high energy side is due to C = O stretch. It indicates some phenolic –OH groups are converted into keto groups, as shown in the following reaction Scheme 1. In contrast, POF-800 showed low intense band due to OH stretching as well as maximum dehydration at high temperature. The most important observation is the loss of the peak at 1620 cm\(^{-1}\). As the quinonoid becomes centrosymmetric, such a vibration becomes forbidden.

TGA and derivative spectra were depicted in Fig. 1(b). POF and POF-800 exhibit slight weight loss at an initial temperature around 120 °C due to the evaporation of residual solvent present in the sample. POF shows second weight loss at 450 °C which might be the degradation of the polymer backbone chain. Also, POF sample shows a nearly complete mass loss in the range between 400 and 600, suggesting that...
they are mainly composed of carbon with a low amount of oxygen. Whereas, POF-800 shows increased stability when compared with POF. It clearly illustrates that after the treatment of carbonization the stability of the material was increased and shows the carbon yield of 19%.

To explore the porous nature of the prepared material in elaborate,

Fig. 2. SEM images of POF and POF-800 with different magnifications.

Fig. 3. TEM images of POF and POF-800 with selected area diffraction (SAD) pattern.
nitrogen sorption (adsorption and desorption) isotherm was achieved, and it is illustrated in Fig. 1(c). Both the materials, POF and POF-800 confirmed type IV with H2 hysteresis loop according to the IUPAC classification, which was ascribed to their predominantly mesoporous pore structure [23]. At low partial pressure (P/P0 = 0.01), no increase of the adsorption was observed in both the materials. It clearly explains both the synthesized material possesses the absence of micropores. At high partial pressure (P/P0 = 0.61–0.99), increase in nitrogen adsorption explained the existence of interparticle mesoporosity in the materials [24]. For POF, the adsorption and desorption isotherm is not coinciding due to voids. POF and POF-800 show regular mesopores between approximately 30 and 39 nm and other weak pore size distributions, as shown in Fig. 1(c) inset. The POF and POF-800 exhibit the surface area of 162.34 and 352 m2 g−1, respectively. After direct carbonization process, porous carbon materials were obtained without much destroyed their structure showing an increased surface area of 352 m2 g−1 [25].

Raman analysis was attained on POF-800 in order to examine the degree of graphitization within the sample (Fig. 1(d)). It exhibits two main peaks at 1345 and 1575 cm−1, corresponding to D and G bands, respectively. D band signifies the defect or disordered band, whereas G band illustrates the in-plane stretching vibration of sp2 carbon hybridization [26–28]. The graphitization degree of carbon materials, as manifested by the relative intensity ratio of D band to G band (ID/IG), is determined to be 1.06, revealing the presence of more defects present in the synthesized sample.

The initial electrophilic substitution is accompanied by dehydration to form the brown colored product, which on high-temperature fusion yielded a black colored product. The reaction accounts for the reduction of the intensity of –OH stretching in the FTIR spectrum (Fig. 1). The reaction for only one position of phloroglucinol is shown in Scheme 1.

The SEM images of POF and POF-800 with different magnifications were shown in Fig. 2. POF showed particles with varying morphologies. Few of them were of rods. Whereas, SEM images of POF-800 exhibited aggregates of fine threads as well as particles. Formation of fine threads is ascribed to fused rings as shown in the reaction Scheme 1. In POF, as
there are much hydroxyl groups, there might be much interchain interaction leading to a large association. So, very large, dense morphologies were seen. In POF-800, most of the hydroxyl groups were lost resulting in the formation of threads and tiny spheres.

The detailed morphological characteristics of the prepared materials were further confirmed by TEM analysis. Fig. 3 shows characteristic TEM images of POF and POF-800 with the SAD pattern. The attained TEM images are perfectly reliable with the SEM results (Fig. 2), illustrating that the POF showed dense aggregates in association with rods. The SAD establishes amorphous nature. The TEM image of POF-800 showed aggregates of tiny particles with fine threads. The SAD showed amorphous nature like POF. The diameters of the threads and particles were found to be distributed randomly in the range of 50 to 80 nm. These threads and particles are well connected to form a bulk percentage of mesopores, which facilitates ion transport throughout the charge-discharge process. The images obtained from SEM and TEM clearly illustrated that the POF-800 have a continuous thread-like context and entirely inter-connected with meso and macropores ranging from several micrometers to nanometers. Such highly inter-connected mesoporous structure could allow passage of electrolyte in the porous carbon by reducing the molecular diffusion limitations, subsequently confirming a high rate capability [29–31].

After pyrolysis, there was still over 13.78% oxygen remained to signify the existence of oxygen holding functional groups (-OH and \(-\mathrm{C}=\mathrm{O}\)) in the prepared carbon material (POF-800), which was in good agreement with the FT-IR results and Scheme 1. The relative atomic percentages or composition of carbon and oxygen heteroatom in POF and POF-800 were estimated by XPS survey spectrum (Fig. 4(a)). The high intensity of O 1 s peak further verifies the abundant oxygen species exist in POF and POF-800. The core level XPS spectra further disclose the chemical nature of the heteroatom (oxygen) in the POF and POF-800 material was revealed in Fig. 4(b) and (c). In the carbon 1 s spectra (Fig. 4(b)), for POF peaks positioned at the binding energies of 284.5, 285.2 and 286.7 represent the \(\mathrm{C}=\mathrm{C}\) (sp\(^2\) carbon atoms), \(\mathrm{C}-\mathrm{O}/\mathrm{C}^\cdot\cdot\cdot\mathrm{C}-\mathrm{OH}\) and \(\mathrm{C}=\mathrm{O}\), correspondingly. Whereas for POF-800 peaks located at the eV values of 284.7, 285.7 and 286.8 corresponds to \(\mathrm{C}=\mathrm{C}\), \(\mathrm{C}-\mathrm{O}/\mathrm{C}^\cdot\cdot\cdot\mathrm{C}-\mathrm{OH}\), and \(\mathrm{C}=\mathrm{O}\), respectively. O 1 s spectra of POF and POF-800 was demonstrated in Fig. 4(c) and it is deconvoluted into two peaks. For POF the peaks of 533.6 and 532.2 eV agree with the binding energies of \(\mathrm{C}=\mathrm{O}\) quinonoid group and \(\mathrm{C}^\cdot\cdot\cdot\mathrm{OH}\) phenolic group. While for POF-800,
the peaks of 533.5 and 531.8 eV in O 1 s spectra corresponds with the C=O and C–OH groups, correspondingly. The presence of oxygen (heteroatom) in the POF-800, which facilitate charge transfer in the majority and at the interface of electrolyte-electrode [32].

Electrochemical performances of the as-prepared POF-800 electrode was estimated by a three-electrode system in an aqueous 6 M KOH electrolyte. Fig. 5(a) shows the cyclic voltammogram (CV) of POF-800 were evaluated at a diverse scan rate (from 2 to 200 mV s$^{-1}$) ranging the potential from $-1.0$ to $-0.1$ V vs. Ag/AgCl electrode. They exhibited quasi-rectangular profile manifesting ideal electric-double layer capacitance (EDLC) performance. More importantly, CV curves almost keep the quasi-rectangular profile even at 200 mV s$^{-1}$ scan rate illustrating that the more effective ion transfer and the quick charge response ability within the POF-800 electrode. Fig. 5(b) portrays the GCD curves of POF-800 electrode at varying the current density from 0.25 to 10 A g$^{-1}$ and it was a more precise technique to estimate the value of specific capacitance. All GCD traces depict a closely linear and symmetrical appearance, implying good EDLC behavior and electrochemical reversibility and it was more consistent with the obtained result of the CV curves. Fig. 5(c) shows the EIS curve of POF-800 electrode between 0.01 and 0.1 Hz. At the region of high frequency, the charge transfer resistance ($R_{ct}$) and the electrolyte contact resistance ($R_e$) and are imitated by the radius of the high-frequency arc on the real axis and the intercepts of the Nyquist plots, respectively [33]. In the low-frequency region, a much steeper line illustrates quicker ion diffusion in POF-800 electrode. The maximum specific capacitance of the POF-800 electrode was 50.1 F g$^{-1}$ calculated from the discharge curve of 0.25 A g$^{-1}$. The specific capacitance (Fig. 5(d)) values gradually decreasing with the increasing current density and it was associated with the increase of the diffusion limitation.

The electrochemical phenomena of the POF-800 electrodes were examined in a full cell (symmetric cell) configuration using aqueous 6 M KOH as the supporting electrolyte. First, the CV curves (Fig. 6(a)) in the numerous operating potential windows from 0 to 1.5 V at a scan rate of 20 mV s$^{-1}$, to realize the device polarization and the electrochemical stability of the POF-800 electrodes. It exhibits quasi-rectangular shaped CV traces up to a region of 0 to 1 V. However, an increment in the potential window, there was small hump was observed at 1. 1 V, 1.3 V and 1.5 V indicative of the pseudocapacitance dedicated by the presence of heteroatom (oxygen) [34]. This present study clearly reveals that the POF-800 SSC device can run over a potential window of 1.5 V with outstanding electrochemical reversibility without a sign of
any evolution. Fig. 6(b) depicts the CV curves of the fabricated POF-800 SSC measured at varying the scan rate from 2 to 200 mV s^{-1}. The shape of CV profiles appearances quasi-rectangular nature representing the nearly ideal capacitive nature of POF-800. Also, the current was increased in the CV traces with an increasing scan rate from 2 to 200 mV s^{-1} proposes the exceptional capacitive phenomena of the POF-800 [35]. Fig. 6(c) shows the charge-discharge traces of the POF-800 SSC determined at different current density. The CD traces exhibit symmetric behavior over all the current densities measured for the POF-800. From Fig. 6(c), it is obvious that the high current density results in fast charging and discharging time while at the lower current density adduced improved charging and discharging profile in the POF-800 SSC [36].

The EIS analysis of the POF-800 SSC was achieved over the frequency ranging from 0.01 to 0.1 Hz at an amplitude of 5 mV, to explore the essential charge transfer kinetics happened at the electrode-electrolyte interfacial region. The Nyquist plot of the device demonstrates the small R_s and R_w impedance of 0.58 and 6.18 Ω, and the plot shows a vertical line in the low-frequency region (Fig. 6d), certifying the low ion diffusion resistance and Warburg resistance, which means the fast and efficient ionic transport in the aqueous 6 M KOH electrolyte [37].

A specific cell capacitance of 46.3 F g^{-1} was measured from the charge-discharge traces at a persistent discharge current density of 0.25 A g^{-1} from which the assessed specific capacitance of the single POF-800 electrode was found to be 50.1 F g^{-1}. The change in the specific capacitance with respect to the current density of the POF-800 SSC was given in Fig. 7(a). In the high current density (10 A g^{-1}), the POF-800 SSC delivered a capacitance of 6.7 F g^{-1} which almost retained 14.47% of the initial capacitance with an increase of 40 fold in current density, thus signifying the better rate capability of the POF-800 SSC [38,39]. Fig. 7(b) shows the Ragone plot of the POF-800 SSC which displays a high energy density of 14.48 Wh kg^{-1} at a specific power density of 375.02 W kg^{-1} when measured at a constant current density of 0.25 A g^{-1}. With an increase of 40 fold in current density, the POF-800 SSC produced an energy density of 2.09 Wh kg^{-1} at a power density of 15,048 W kg^{-1}, revealing a moderate rate ability of the POF-800 SSC.

The cyclic life of the supercapacitor device is one of the most important criteria to determine their usage in the practical applications [40]. Fig. 7(c) represents the cyclic stability of POF-800 SSC over 5000 cycles (measured at a charge density of 0.5 A g^{-1}). Capacitance retention of 96.6% of its initial capacitance has been retained after 5000 cycles and it clearly suggests the good stability of the POF-800 SSC. This is also buoyed by the SEM image of POF-800 electrode obtained after 5000 CD cycles and it was described in the Fig. 7(c) inset. The morphology of the fine threads with particles was well-maintained and the POF-800 that is active material was still attached to the nickel foam,
illustrating the outstanding stability of the prepared material.

4. Conclusion

In conclusion, we have successfully synthesized novel pores enriched carbonaceous polymeric organic framework by a solvothermal method using phloroglucinol and terephthaldehyde as a pre-cursor and subsequent pyrolysis for symmetric supercapacitor applications. The synthesized POF and POF-800 exhibit thread and micro particles like morphology confirmed by SEM and TEM analysis. The thermal stability of the materials was confirmed by TGA. The prepared POF-800 possess surface area of 352 m² g⁻¹, with a maximum specific capacitance of 50.1 F g⁻¹ at 0.25 A g⁻¹ in three-electrode systems. Moreover, the fabricated symmetric supercapacitor delivers moderate energy density of 14.48 Wh kg⁻¹ at a specific power density of 375.02 W kg⁻¹, which are higher than most previously published aqueous carbon-based supercapacitors. The device also showed excellent electrochemical stability upon 5000 charge-discharge cycles. These encouraging results demonstrate that POF based carbon materials open a new avenue for energy storage materials and its applications.

CRediT authorship contribution statement


Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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References


Scheme 1. Reaction protocol of POF and POF-800 from phloroglucinol and terephthaldehyde.