### **RESEARCH ARTICLE**

## **Electronics**

# An electrical double-layer supercapacitor based on a biomassactivated charcoal electrode and ionic liquid with excellent chargedischarge cycle stability

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Abstract: Supercapacitors that exhibit high power density and safety are emerging as alternative energy storage devices. The construction and performance of a supercapacitor using the ionic liquid, triethylammonium thiocyanate, as the electrolyte and biomass-activated charcoal films as the electrode are described. Enhancements in both energy and power density were observed even for 10,000 charge-discharge cycles. The fabricated supercapacitor with ionic liquid and activated charcoal-based electrodes showed an impressive specific capacitance retention of 142% even after 10,000 cycles at a scan rate of 500 mv s<sup>-1</sup>, which is attributed to the clearing of ion conducting pathways and enhanced charge transport with increasing temperature. Impedance analysis confirmed the reduction of resistive losses with increasing cycle numbers. The initial energy and power densities of the Electrical double-layer capacitance (EDLC) were 0.926 W h kg<sup>-1</sup> and 5681 W kg<sup>-1</sup>, and they showed 42.2 %and 60.6 % increments after supercapacitors cycles. The study reveals low-cost biomass-based activated carbon electrodes and trimethylamine thiocyanate can be used to prepare supercapacitors with remarkable cycling performances.

Keywords: Activated carbon, supercapacitor, triethylammonium thiocyanate

#### INTRODUCTION

The rapid increase in energy consumption is a major reason for many researchers to focus on finding sustainable energy sources and developing energy conversion and storage techniques. Renewable energy sources such as wind, solar, hydropower and geothermal are promising resources to conserve degradable energy sources (Fridleifsson, 2001; Panwar et al., 2011; Kumar et al., 2016). However, the main issue with the utilization of most renewable energy sources is the intermittency of the energy supply. This can be overcome by using reliable energy storage technologies. The most common energy storage methods are batteries, supercapacitors, and H<sub>2</sub> storage (Scrosati & Garche, 2010; Lucia, 2014; Poonam et al., 2019). When it comes to energy storage methods, energy density, power density, durability and long cycle life are some of the key factors that determine the quality of the device. Lithium-ion batteries (LIBs) are one of the most versatile devices to store energy. LIBs have a high energy density, but it has numerous drawbacks, including short cycle life, harmful compounds used in manufacturing, the inclusion of highly flammable substances and long charging time. Supercapacitors have certain characteristics, including quick charging, long cycle life, and high power density, which make them suitable for use in practical applications (Portet et al., 2005; Brousse et al., 2007). Hence, they appear to be one of the most promising replacements for batteries for certain applications. To enhance the practical viability of supercapacitors, improving energy density, durability, and cycle stability are the main areas of focus in ongoing supercapacitor research.





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In supercapacitors the two main charge storage mechanisms are electrical double-layer capacitance and pseudo capacitance (Karthikeyan et al., 2021). Electrical double-layer capacitance (EDLC) is based on charge accumulation at the electrode-electrolyte interface due to electrostatic forces, forming a double layer of charges. Carbon-based materials including carbon nanotubes, porous carbon, templated carbon, and activated carbon are commonly used as electrode materials for EDLC-type supercapacitors (Gamby et al., 2001; Fuertes et al., 2005; Pan et al., 2010; Yin et al., 2020). In pseudocapacitors, charge is stored through Faradaic reactions (Karthikeyan et al., 2021). Conducting polymers and metal oxides are well-known electrode materials for pseudocapacitors (Chen et al., 2014; Bryan et al., 2016). In these materials, capacitive processes occur due to fast surface redox reactions, giving them capacitive properties; however, they show poor cyclability (Abruña et al., 2008).

Two main functional components in a supercapacitor are the electrode and the electrolyte. Activated carbonbased electrodes offer higher cycle life in addition to their low cost. However, most of the activated carbons commercially available are produced from precursors derived from fossil fuels (Abioye & Ani, 2015). Attempting to use green carbon materials, which are agro-industrial waste in device applications gives several direct and indirect advantages. The utilization of biomassderived activated carbon electrodes for supercapacitor fabrication reduces their production cost. The electrode material utilized in this work was fabricated using activated carbon powder made from coconut shells.

In general, ionic liquids offer many advantages over conventional aqueous electrolytes or volatile organic solvent-based electrolytes for the devices, though their conductivity is lower than that of liquid electrolytes. To fabricate EDLC with longer cycle life and stability, such ionic liquids are an ideal candidate. Trimethylamine thiocyanate (TAT) is primarily used as a crystal growth inhibitor of CuI crystal to improve the performance in solid-state dye-sensitized solar cells (Kumara et al., 2002). However, novel TAT-based electrolytes have not been widely studied as an electrolyte for supercapacitors One of the main issues in batteries and supercapacitors is performance degradation with charge-discharge cycling. In a previous study, it was demonstrated that there is a possibility of utilizing TAT ionic liquid as an electrolyte for the activated carbon-based supercapacitor (Medagedara et al., 2022). In this study, our primary objective is to investigate the performance degradation issue associated with charge-discharge cycling in supercapacitors. Specifically, we investigate the potential of utilizing trimethylamine thiocyanate (TAT) ionic liquid as an electrolyte to enhance the electrochemical performance and cycle stability of activated carbon-based supercapacitors. Through a series of electrochemical tests including cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS), we aim to demonstrate the effectiveness of TAT-based electrolytes in improving both energy and power density, even over an extended cycling period of 10,000 charge-discharge cycles. The study reveals a 142 % capacity improvement after 10,000 cycles, which is a good value for a biomass-derived carbon electrode-based supercapacitor that shows an extremely high power density of 9124 W kg<sup>-1</sup> (Abioye & Ani, 2015; Dos Reis et al., 2020; Patel et al., 2021).

#### MATERIALS AND METHODS

Titanium plates with dimensions of  $2\text{cm}\times1\text{cm}\times0.45\text{mm}$ were used as current collector plates. Ammonium thiocyanate (NH<sub>4</sub>SCN, 98.0% (m/m) assay) and dichloromethane (CH<sub>2</sub>Cl<sub>2</sub>, 99.5% (m/m) assay) were purchased from Fujifilm Wako Pure Chemical Corporation, Osaka, Japan. Triethylamine (C<sub>6</sub>H<sub>15</sub>N, 99.0% purity) was purchased from Daejung Chemicals, Siheung-si, South Korea. Hexane (C<sub>6</sub>H<sub>14</sub>, 99.0% purity) was procured from Sigma-Aldrich, St. Louis, Missouri, United States. Polyvinylpyrrolidone (PVP) was obtained from Research-Lab Fine Chem Industries, Mumbai, India. Medium retention filter papers (model-F1001, retention range 10-13µm) were obtained from Chmlab, Barcelona, Spain.

# Ionic liquid electrolyte triethylammonium-thiocyanate

To begin with, the moisture in ammonium thiocyanate was removed by placing it on top of a hot plate for 30 min at 90 °C. Anhydrous ammonium thiocyanate was then combined with triethylamine, (triethylamine in 25% excess of the stoichiometric quantity). Thereafter, the mixture was heated for 3 min at 120 °C. It is necessary to keep heating the mixture until all of the NH<sub>3</sub> has been expelled from the mixture. Triethylammonium thiocyanate is formed during this reaction, as shown in the equation below.

$$\begin{array}{l} (C_2H_5)_3N_{(l)} \\ (25\% \text{excess}) \end{array} + NH_4SCN_{(S)} \quad (C_2H_5)_3NH^+_{(l)} + SCN^-_{(l)} + NH_{3(g)} \end{array}$$

 $(C_2H_5)_3NH^+_{(l)}$  and  $SCN^-_{(l)}$  ions separate from the reaction mixture as these ions are insoluble in triethylamine. The

ionic component settles at the bottom of the vessel due to its high molecular mass. The ionic components including unreacted  $NH_4SCN$  and  $(C_2H_5)_3N$  were then extracted from the mixture.

The solution was washed with hexane three times to ensure that there was no unreacted  $(C_2H_5)_3N$  present; excess dichloromethane was then added to the resultant product. If there was any unreacted NH<sub>4</sub>SCN present in the solution a white-colored precipitate would be formed. The supernatant was obtained by centrifugation and the excess dichloromethane was removed by evaporation to obtain colorless triethylammonium-thiocyanate. Finally, the colorless ionic liquid was dried under vacuum for 1 h at 70 °C, followed by 30 °C for 5 d (Konno *et al.*, 2004; Medagedara *et al.*, 2022).

#### Activated carbon electrodes

Initially, coconut shells were thoroughly cleaned by removing fibrous debris from the surface followed by burning in a box furnace under minimum-oxygen conditions. The burnt coconut shells were heated at 900 °C for 20 min in a box furnace. The charcoal was then dumped into a distilled water bath to quench, dried, and finally disc-milled into a fine powder (Keppetipola *et al.*, 2021). This activated carbon sample was characterized using an X-ray ( $\lambda$ =1.5406 Å) diffractometer (XRD; RigakuUltimaIV X-ray powder diffractometer) and Raman Spectroscopy.

The following steps were taken to create activated carbon-coated current collector plates: an activated carbon layer was formed on the surface of the current collector plate using the spray pyrolysis method. To accomplish this, a suspension of activated carbon and PVP was prepared consisting of 1 g of activated carbon powder, 0.05 g of PVP, and 10 ml of isopropanol. The suspension was then sonicated for 10 min. As shown in Figure 1, the resulting solution was sprayed onto titanium current collector plates. The solution-coated current collector plates were then sintered at 200 °C for 20 min.



Figure 1: Schematic diagram for the process of making a supercapacitor with TAT electrolyte.

#### Fabrication of supercapacitors and characterization

Initially, fabricated electrodes were wetted with TAT electrolyte and sandwiched with a membrane that can serve as a separator between the electrodes. This membrane is permeable to the ions present in the electrolyte. The characterization of the supercapacitor was done using a Metrohm Autolab Potentiostat/Galvanostat. Current collector plates were connected to the Metrohm Autolab Potentiostat/Galvanostat and the cyclic voltammograms (CV) readings were taken. To investigate the stability of the cell, 10,000 CV cycles were performed at a scan rate 500 mV s<sup>-1</sup> potential and retention of capacitance was checked. The following equation was used to calculate the specific capacitance of the cell:

$$C = \frac{1 \int IdV}{2m \,\Delta V \frac{dV}{dt}} \qquad \dots (1)$$

Where *m* is the mass of the activated carbon layer on the electrode surface, *I* is the current,  $\Delta V$  is the potential range used, and dV/dt is the potential scan rate used for the CV experiment.

The following equations were used to calculate the energy density and the power density of the supercapacitor:

$$E = \frac{1}{2}CV^2 \qquad \dots (2)$$

$$P = \frac{V^2}{4R} \qquad \dots (3)$$

Where C is the specific capacitance of the supercapacitor, R is the equivalent series resistance for the two electrode system, and V is the potential window.

#### **RESULTS AND DISCUSSION**

#### Characterization of activated carbon

XRD peaks indicate the amorphous form of activated carbon. Based on the positions of the broad peaks at  $2\theta = 23.5^{\circ}$  and  $43.7^{\circ}$ , they are consistent with diffractions from the (002) and (100) planes of the activated carbon standard XRD pattern. These peaks correspond to d-spacing of 3.8 and 2.1 Å (JCPDS 75-1621).

As seen in Figure 2b, two primary bands are visible in the Raman spectra of activated carbon powder. The bands

at 1350 cm<sup>-1</sup> and 1600 cm<sup>-1</sup> correspond to the D and G bands, respectively. The two 1st order Raman shifts in the 1000–1700 cm<sup>-1</sup> range are related to sp<sup>2</sup> hybridized carbon in the material. The graphite band (G band) is concerned with perfect graphitic vibration modes, whereas the defect band (D band) is concerned with disordered graphite (Islam et al., 2019; Thapliyal et al., 2022). The presence of disordered sp<sup>2</sup> -hybridized carbons is evident from the broader D band in Figure 2b. By comparing the intensity values of the bands  $I_D/I_G$  where  $I_D$  and  $I_G$  are the intensities of the D and G bands, respectively, we can measure the level of structural defects, the degree of graphitization or decreased crystallinity of the activated transition from sp<sup>2</sup> hybridization to sp<sup>3</sup> carbon sample (Cuesta et al., 1994). The sample's  $I_D/I_G$  ratio is 0.84, which indicates there are fewer structural deficiencies in this substance.

#### Characterization of supercapacitor

The cyclic voltammograms, taken at 5, 10, 20, 50, 100, 250 and 500 mV s<sup>-1</sup> are shown in Figure 3. The nearly rectangular behavior of the CVs shown, particularly for slow scan rates, indicates the EDLC-type charge storage mechanism in the SCs. It can be observed that the rectangular shape of the CV curve is lost when the scan rate increases, which can be due to the relaxation effects of deep penetrating charge carriers. In other words, slow scan rates give sufficient time for deep penetrating charge carriers to diffuse into pores thereby enhancing the effective area of the double layer, which finally contributes to improve the capacitance. Therefore, specific capacitance decreases with an increasing scan rate due to polarization relaxation as shown in Table 1.



Figure 2: X-ray diffraction spectra of the activated carbon powder derived from coconut shell charcoal, and (b) Raman spectrum of the activated carbon powder derived from coconut shell charcoal.

Additionally, it can be observed that the cycling current increases with the increasing CV scan rate without reaching a plateau as seen for the lower rates. This may be a result of a rapid increase in potential difference.



Figure 3: The cyclic voltammograms taken at different scan rates.

 Table 01:
 The specific capacitance values of the prepared SC at different scan rates

Scan rate (mV s <sup>-1</sup> )	Area under the CV curve (mV A)	Specific capacitance (F g <sup>-1</sup> )
5	1.47	36.8
10	2.67	33.5
20	4.72	29.5
50	8.74	21.9
100	10.9	13.5
250	20.2	10.1
500	26.7	6.68

The study of the cycle life of supercapacitors is important to investigate the stability of devices. Figure 4a shows CV curves of initial and 10,000<sup>th</sup> scan cycles measured at 500 mV s<sup>-1</sup> scan rate, which was used to investigate the cycle stability of the fabricated supercapacitors. In this study, a rather high scan rate of 500 mV s<sup>-1</sup> is used to check the device functionality under rapid charging and discharging. A previous study demonstrated that a high capacity retention of approximately 94.4% can be achieved when using a scan rate of 100 mV s<sup>-1</sup> for 1000 cycles (Medagedara et al., 2022). In the present study, cells were tested with a large number of scan cycles but at higher scan rates. Figure 4b shows selected CVs for the 1<sup>st</sup>, 1000<sup>th</sup>, 2000<sup>th</sup>, 3000<sup>th</sup>, 4000<sup>th</sup>, 5000<sup>th</sup>, 6000<sup>th</sup>, 7000<sup>th</sup>, 8000th, 9000th and 10,000th cycle for the supercapacitor with TAT electrolyte at a scan rate of 500 mV s<sup>-1</sup>. The enclosed area of the CV curve gradually increases with the number of CV scan cycles indicating the specific capacitance increment as given in Table 2.

The CV curve in Figure 4b shows an increase in the current flows through the device during charging and discharging with increasing number of cycles. The electrodes and the electrolyte, can heat up due to increased current, resulting in improved charge transport dynamics in the electrolyte and electrode as the number of cycles increases. Further, this can also be attributed to a reduction in internal resistance due to the large number of consecutive cycle repetitions conducted with a relatively high rate, which clears ion moving paths on the electrode surface. In addition, the initial CV cycles can clean or pretreat the electrode (McCarthy *et al.*, 2014). This effect can finally improve the polarization of charge carriers resulting in an enhancement of the specific capacitance. Such variations, that take place during the



Figure 4: (a) Comparison of the initial and final cyclic volumetric changes of the cell after 10,000 cycles. (b) Selected cyclic voltammograms of 1000 steps 500 mV s<sup>-1</sup>.

cycling process, are further analyzed by taking EIS and GCD measurements before and after taking CVs.

Cycle number	Area under the CV curve (mV A)	Specific capacitance (F g <sup>-1</sup> )	
1 <sup>st</sup>	26.7	6.67	
1000 <sup>th</sup>	27.4	6.85	
2000 <sup>th</sup>	29.8	7.46	
3000 <sup>th</sup>	32.2	8.06	
4000 <sup>th</sup>	33.1	8.29	
5000 <sup>th</sup>	34.4	8.60	
6000 <sup>th</sup>	37.6	9.39	
$7000^{\text{th}}$	37.2	9.30	
8000 <sup>th</sup>	37.4	9.35	
9000 <sup>th</sup>	37.5	9.38	
10,000 <sup>th</sup>	37.9	9.48	

 
 Table 2:
 Variation of specific capacitance value and the enclosed area of the cyclic voltammograms (CV) with the number of cycles.

Figure 5 illustrates the GCD curves of the TAT supercapacitor at various current densities. Figure 6 shows the GCD curve taken at 1 A g<sup>-1</sup> current density for 4 cycles before and after taking 10,000 CV cycles. During the discharge state, a small initial ohmic drop is caused by the cell's series resistance. The key factor causing this loss is the initial resistive loss at the electrodeelectrolyte interface (Qu et al., 2016). In addition, a significant decrease in the ohmic drop is observed, which can be attributed to decreased resistance. The triangular symmetric shape of GCD depicts (apart from the initial IR drop) the EDLC behavior of the supercapacitor (Vaquero et al., 2013). After the cycling process (Figure 6b), the supercapacitor's charging and discharging time is longer compared to that of fresh cells (Figure 6a); this can be attributed to the improved charge storage capacity of the cells with continued CVs. Since the current density is constant, it takes a longer time to charge and discharge more charges. Figure 6 and the data given in Table 3 serve as evidence of the excellent stability of the EDLC fabricated in this study even after 10,000 CV cycles.



Figure 5: The GCD curves of the TAT supercapacitator at different current densities (a) 0.5, (b) 1.0, (c) 1.5, and (d) 2.0 A g<sup>-1</sup>.



Figure 6: The GCD curves at 1 A g<sup>-1</sup> current density, (a) before taking 10,000 cycles, and (b) after taking 10,000 cycles.

 Table 3:
 Specific capacitance, energy density and power density values of the supercapacitor before and after 10,000 cycles.

Number of cycles	Area under the CV curve (mV A)	Specific capacitance (F g <sup>-1</sup> )	Energy density (W h kg <sup>-1</sup> )	Power density (W kg <sup>-1</sup> )
Initial	26.7	6.670	0.926	5681
After 10000	37.9	9.481	0.951	9124

Equations (2) and (3) were used to calculate the energy and power densities of the supercapacitor. Table 3 shows the area under the CV curve, specific capacitance, energy density and power density of the supercapacitor before and after taking CVs for 10,000 cycles. More importantly, all of these parameters had higher values after 10,000 CV cycles compared to their initial values. The results reveal the excellent stability of the supercapacitors prepared, which can be mainly attributed to the selection of appropriate electrolyte and electrode materials.

Figure 7 depicts the variation of specific capacitance and the energy density of the EDLC with the number of cycles. As shown in Figure 7, there is a significant increase in specific capacitance from 6.67 F g<sup>-1</sup> to 9.48 F g<sup>-1</sup> in the first 6000 cycles. However, after 6000 cycles, the specific capacitance has become stable at around 9.40 F g<sup>-1</sup>. From the initial state to the final state, the specific capacitance of the supercapacitor increases with the number of cycles, from 6.67 F g<sup>-1</sup> to 9.48 F g<sup>-1</sup>, indicating a 142% enhancement compared to its initial value. The initial energy and power densities of the EDLC are 0.926 W h kg<sup>-1</sup> and 5681 W kg<sup>-1</sup>, and they increased to  $1.317 \text{ W h kg}^{-1}$  and  $9124 \text{ W kg}^{-1}$ , respectively, after 10,000 cycles. These were 42.2 % and 60.6 % increments of energy and power densities of the EDLC, respectively.



Figure 7: Variation of specific capacitance and the energy density values with the number of cycles.

Figure 8a shows the graph of the imaginary part (Z'') of the impedance against the real part (Z') of the cell after 0, 2000, 4000 and 10,000 cycles. The shift of the curves towards lower Z' values as the number of cycles increases is evidence of a decrease in transport resistance. The real axis intercept of the curve indicates the equivalent series resistance (ESR) of the supercapacitor, which decreases with the number of cycles from 11  $\Omega$  to 6.8  $\Omega$  in this study. The EIS data proves the reduction of resistance with the increasing number of cycles. This reduction in internal resistance is due to the large number of cycle repetitions conducted with a relatively high rate, which causes the clearing of ion moving paths on the electrode surface or enhanced ion penetration. In addition, the reduction of resistance can happen due to an increase in temperature resulting from the heat dissipated from the sequential and faster cycling process. The first 2000 cycles reduce the internal resistance by 2.4  $\Omega$ . In the beginning, electrodes show some resistance to ion movements, but after 2000 cycles it seems to be depleted. Therefore, the observed increase of super-capacitive parameters, with the increasing number of CV cycles given in Table 3, can be attributed to the reduction of resistive losses. The coulombic efficiency begins at 73% and stabilizes at 99% after 1000 cycles, as shown in Figure 8b.



Figure 8: (a) Nyquist plot of TAT supercapacitor after 0, 2000, 4000 and 10,000 cycles, (b) coulombic efficiency variation with number of cycles

Electrochemical impedance spectroscopy was used to determine the frequency-dependent complex capacitance of the EDLC. The following equations (4 and 5) are used to calculate the frequency-dependent real (C') and imaginary (C'') parts of the net capacitance:

$$C' = \frac{-z''}{\omega(z'^2 + z''^2)} \qquad ...(4)$$

$$C'' = \frac{Z'}{\omega(Z'^2 + Z''^2)} \qquad ...(5)$$

The calculated real and imaginary specific capacitances

are given in Figures 9a and 9b, respectively, as a function of angular frequency. Figures 9c and 9d show  $\log C'$  $\log C''$  against  $\log \omega$ . Here C' and imaginary C'' represent the resultant bulk and double-layer capacitances. In these curves, the high-frequency capacitances are related to the bulk capacitance of the cell while the low-frequency values correspond to the double-layer capacitance. In order to calculate frequency independent double layer capacitance (static capacitance), we need to determine  $C'_{(\omega=0)}$ . The respective logarithmic curves in Figure 9 shows a linear relationship. Therefore, the data were fitted with the equations  $\log(C') = m \log(\omega) + K$  and  $\log(C'') = m'\log(\omega) + K'$  to understand the behavior. Calculated m and K parameters are given in Table 4.



Figure 9: The frequency dependence of the real part (a) and the imaginary part (b) of the specific capacitance after 0, 2000, 4000 and 10,000 cycles. The logarithmic frequency dependence of the real part (c) and the imaginary part (d) of the specific capacitance after 0, 2000, 4000 and 10,000 cycles.

	Cycle Number	Gradient (m)	$\log(C) (\mathrm{F} \mathrm{g}^{-1})$	Static $C$ (F g <sup>-1</sup> )
Real ( <b>C'</b> )	0	-1.28	0.79	6.14
Imaginary ( <b>C''</b> )		-0.95	1.09	12.41
Real ( <b>C'</b> )	2000	-1.24	0.87	7.50
Imaginary ( <b>C''</b> )		-0.94	1.15	14.19
Real ( <b>C'</b> )	4000	-1.23	0.88	7.63
Imaginary ( <b>C''</b> )		-0.95	1.24	17.25
Real ( <b>C'</b> )	10,000	-1.19	0.89	7.76
Imaginary ( <b>C''</b> )		-0.94	1.22	16.78

**Table 04:** The slope, intercept, and constant (k) values derived from the graph log(C) vs. $log(\boldsymbol{\omega})$ .

#### CONCLUSION

The results of this study demonstrate that TAT is a promising electrolyte for creating supercapacitors with high durability, stability and cycle life. The supercapacitor made with TAT and AC-based electrodes exhibited an impressive specific capacitance retention of 142% after 10,000 cycles at a scan rate of 500 mV s<sup>-1</sup>. The increase in specific capacitance from 6.67 to 9.48 F g<sup>-1</sup> may be attributed to the clearance of ion conducting pathways and improved charge transport with the rise in temperature. The use of prominent and stable AC electrodes and ionic liquid electrolytes is a major contributor to the impressive stability. The initial energy and power densities of the EDLC were 0.926 W h kg<sup>-1</sup> and 5681 W kg<sup>-1</sup>, respectively, and they showed increments of 42.2 % and 60.6 % after 10,000 cycles. EIS data analysis reveals that the ESR value of the cell has decreased from 11  $\Omega$  to 7  $\Omega$ , after 10,000 cycles. The increase in EDLC performance with voltametric cycling is a result of the reduction of resistive losses. The study reveals that low-cost biomass-based activated carbon electrodes combined with an ionic liquid can be used to prepare EDLC with excellent cycling performance. This study introduces a method to determine frequencyindependent or scan rate-independent ways to determine the specific capacitance (static capacitance) of EDLCs using complex impedance analysis.

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