Indian Journal of Chemical Technology
Vol. 33, July 2026, pp. 515-522
DOI: 10.56042/ijct.v33i4.33202

Biomass-derived activated carbon from *Cyperus pangorei* for high-performance supercapacitor electrodes

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Received 30 June 2026; accepted 15 July 2026

Activated carbon was successfully prepared from *Cyperus pangorei* through a simple and cost-effective thermal decomposition method using ghee as a carbonization aid. The obtained carbon was annealed at 500 °C for 3 h and characterized by scanning electron microscopy and Fourier transform infrared spectroscopy (FTIR). SEM analysis revealed aggregated carbon particles, while FTIR confirmed the presence of oxygen-containing surface functional groups. The electrochemical performance of the prepared carbon electrode was evaluated using cyclic voltammetry, galvanostatic charge-discharge, electrochemical impedance spectroscopy and cycling stability studies using PVA / Na_2SO_4 gel electrolyte within a potential window of 0–1.5 V. The electrode exhibited a maximum specific capacitance of 476 F g^{-1} and maintained excellent capacitive behaviour even at a high current density of 25 A g^{-1}. The enhanced electrochemical performance is attributed to the combined contribution of electric double-layer capacitance and surface redox activity associated with oxygen-containing functional groups. The results demonstrate that *Cyperus pangorei*-derived carbon is a promising low-cost and sustainable electrode material for supercapacitor applications.

Keywords: Activated carbon, Biomass carbon, *Cyperus pangorei*, Energy storage, Electrochemical performance, Supercapacitor

Introduction

The growing demand for sustainable energy storage systems has stimulated extensive research on advanced electrochemical energy storage devices. Supercapacitors, batteries, and conventional capacitors are widely used in energy storage technologies based on electrochemical energy conversion processes[1-3]. Among them, supercapacitors have attracted significant attention owing to their high power density, rapid charge-discharge capability, long cycle life, operational safety, and environmental friendliness[4]. These characteristics make them suitable for applications in consumer electronics, backup power systems, electric vehicles and renewable energy storage.

The performance of supercapacitors is strongly influenced by the nature of the electrode material. Various electrode materials, including activated carbons, carbon aerogels, carbon nanotubes, graphene-based materials, conducting polymers and transition metal oxides, have been investigated for supercapacitor applications. Recently, biomass-derived activated carbons have attracted considerable attention as sustainable electrode materials for high-performance supercapacitors owing to their low cost, renewability, tunable pore structure and environmental friendliness. Recent reviews have highlighted the significant progress achieved in the synthesis, activation strategies, and electrochemical performance of biomass-derived carbon materials for energy storage applications[5-6].

Activated carbons are among the most widely used electrode materials because of their high specific surface area, excellent electrical conductivity, chemical stability and low cost[7]. Activated carbons can be produced from a variety of carbon-rich precursors, particularly biomass wastes, which offer the advantages of abundance, renewability, and environmental sustainability[8]. Numerous biomass sources such as palm-tree cobs, plum kernels, cassava peel, sugarcane bagasse, rice husks, olive stones, date pits, fruit stones and nutshells have been successfully utilized for the preparation of activated carbons[9].

Cyperus pangorei commonly known as korai grass, is an abundant lignocellulosic biomass containing holocellulose, cellulose, hemicellulose, lignin, waxes, and moisture[10]. Owing to its high carbon content and widespread availability, it represents a promising precursor for the preparation of activated carbon. It contains cellulose, hemicellulose and lignin, which are known to produce a high carbon yield upon thermal decomposition. In addition, the fibrous structure of

Cyperus pangorei facilitates the formation of porous carbon during carbonization, providing a large number of electroactive sites for electrolyte-ion adsorption. The utilization of this agricultural biomass not only reduces waste disposal problems but also offers a sustainable and environmentally friendly route for the production of low-cost carbon electrode materials for supercapacitor applications. The development of porosity in activated carbons can be achieved through physical activation using oxidizing gases such as steam or carbon dioxide or through chemical activation employing activating agents such as phosphoric acid and zinc chloride[11].

In the present work, biomass derived carbon was prepared from *Cyperus pangorei* through a simple thermal decomposition process using ghee as a carbonization aid. To the best of our knowledge, the electrochemical performance of carbon derived from *Cyperus pangorei* using a simple thermal decomposition route with ghee-assisted carbonization has not been systematically investigated for supercapacitor applications. Various biomass precursors, including agricultural wastes, lignocellulosic materials and plant-derived residues have been explored to prepare porous carbons with high surface area and abundant functional groups, which enhance electrolyte ion accessibility and charge storage capability. However, challenges such as controlling pore structure, improving electrical conductivity and developing simple eco-friendly synthesis strategies still limit their practical applications. Therefore the exploration of novel biomass resources and sustainable processing routes remains essential for designing high-performance carbon electrodes.

The present work demonstrates an inexpensive and sustainable approach for converting an abundantly available natural biomass into a high-performance carbon electrode material. The structural and morphological characteristics of the prepared carbon were investigated using Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM). The electrochemical performance was evaluated using cyclic voltammetry, galvanostatic charge-discharge, electrochemical impedance spectroscopy and cycling stability measurements in PVA / Na_2SO_4 semi-gel polymer electrolyte. This study highlights the potential of an unexplored biomass precursor for developing cost-effective and environmentally friendly supercapacitor electrodes.

Experimental Section

Biomass derived carbon was prepared from *Cyperus pangorei* through a thermal decomposition method. Fresh *Cyperus pangorei* was collected from nearby agricultural fields and dried using a solar dryer to remove moisture. The dried biomass was subsequently carbonized in a quartz crucible under atmospheric conditions. During the carbonization process, a small quantity of ghee was added as a carbonization aid to facilitate uniform combustion and enhance the carbon yield. The resulting carbonaceous material was collected and annealed at 500 ºC for 3 h.

The annealing treatment promoted the development of porosity through the selective removal of volatile and reactive carbonaceous species, leading to the formation of carbon with an enhanced porous structure. The obtained carbon powder was then ground thoroughly and used for structural, morphological and electrochemical characterization.

FTIR spectra of the prepared carbon were recorded using a PerkinElmer Spectrum BX II spectrometer in the wave number range of 400–4000 cm^{-1} to identify the surface functional groups present in the material. The surface morphology of the carbon was examined using a TESCAN VEGA-3 LMU scanning electron microscope.

Electrochemical measurements were carried out using a conventional three-electrode system (Fig. S1). The working electrode was prepared by mixing the carbon material, carbon black and polytetra-fluoroethylene (PTFE) binder in a weight ratio of 80:15:5. Ethanol was added to obtain homogeneous slurry, which was uniformly coated onto a graphite sheet (1 cm × 1 cm) and dried at 70 °C for 12 h. The mass loading of the active material was approximately 1 mg.

The prepared electrode served as the working electrode, while a saturated calomel electrode (SCE) and a platinum wire were used as the reference and counter electrodes respectively. Poly vinyl alcohol (PVA) containing 1 g Na_2SO_4 was employed as the gel electrolyte. Electrochemical performance was evaluated using a CHI660D electrochemical workstation. A PVA / Na_2SO_4 gel electrolyte was employed to provide ionic conduction between the working, reference and counter electrodes. Cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), electrochemical impedance spectroscopy (EIS) and cycling stability measurements were performed to investigate the capacitive behaviour of the prepared carbon electrode. The electrochemical measurements were carried out in the potential range of 0–1.5 V. This potential window was selected based on preliminary experiments, which showed stable

voltammetric responses without noticeable gas evolution or electrolyte decomposition.

Results and Discussion

Structural and morphological studies

The FTIR spectrum of the carbon material derived from *Cyperus pangorei* is presented in Fig. 1. The spectrum reveals the presence of several oxygen-containing functional groups on the carbon surface, which are known to influence the electrochemical performance of carbon-based electrodes. The broad absorption band centered at 3450 cm^{-1} is attributed to the O–H stretching vibration of hydroxyl groups and adsorbed water molecules. The band observed at 2910 cm^{-1} corresponds to the C–H stretching vibration of aliphatic carbon species. The absorption bands at 1758 cm^{-1} and 1600 cm^{-1} are assigned to the stretching vibrations of carbonyl (C=O) and aromatic carbon (C=C) groups respectively. The band at 1500 cm^{-1} is associated with aromatic carbon–carbon skeletal vibrations indicating the presence of partially graphitized carbon domains[12].

A prominent absorption band at 1041 cm^{-1} is attributed to C–O stretching vibrations of oxygen-containing functional groups such as alcohols, phenols, esters, and carboxylic acids. The presence of these surface functionalities may enhance the wettability of the electrode and facilitate charge transfer at the electrode–electrolyte interface, thereby contributing to improved electrochemical performance[13].

In the low-frequency region 450–750 cm^{-1} the bands located at 462 cm^{-1} and 591 cm^{-1} are assigned to in-plane and out-of-plane aromatic ring deformation vibrations[14]. The observed functional groups are primarily derived from the lignocellulosic constituents of *Cyperus pangorei* and the carbonization process. The presence of oxygen-containing surface functionalities is expected to provide additional electroactive sites and contribute to pseudocapacitive behaviour during charge storage.

The surface morphology of the carbon material derived from *Cyperus pangorei* was examined using scanning electron microscopy and the corresponding images are shown in Fig. 2. The SEM image reveals the formation of aggregated spherical carbon particles distributed over the surface. The aggregation of these

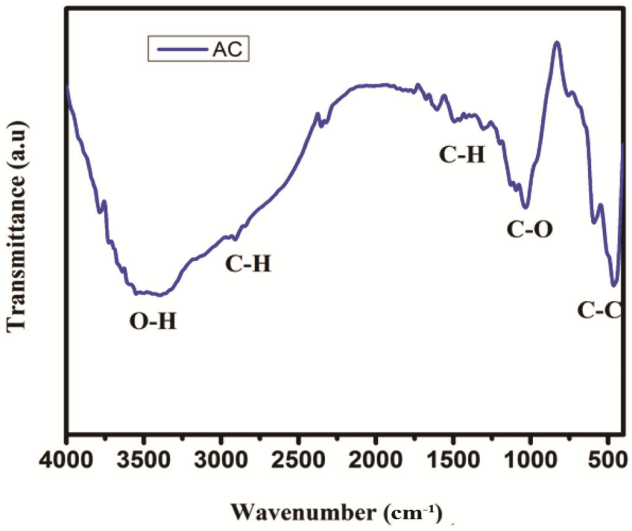

Fig. 1 — FTIR spectrum of the *Cyperus pangorei*-derived carbon electrode

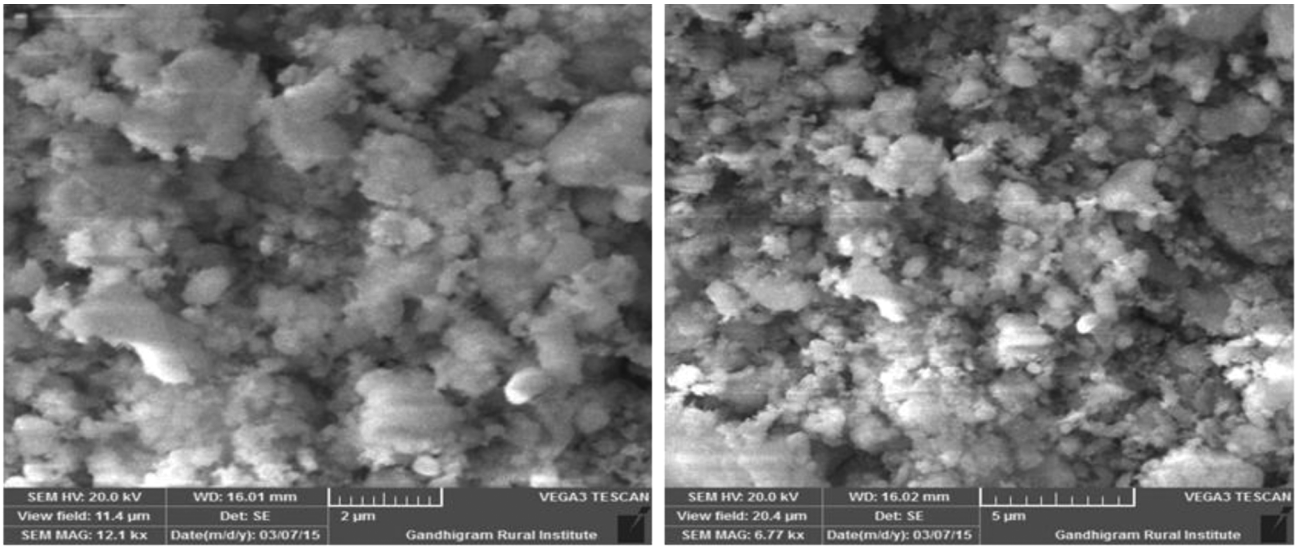

Fig. 2 — SEM images of the *Cyperus pangorei*-derived carbon electrode at different magnifications

particles results in the development of interparticle voids and porous regions, which are beneficial for electrolyte penetration and ion transport during electrochemical processes.

The observed morphology provides a large number of electroactive sites accessible to the electrolyte ions, thereby facilitating charge storage. The aggregation of carbon particles creates interparticle voids that facilitate electrolyte penetration and ion transport. The interconnected carbon particles also contribute to efficient electron transport throughout the electrode material, making the prepared carbon as a promising candidate for supercapacitor applications.

Electrochemical studies

Cyclic voltammetric studies

The cyclic voltagrams of the *Cyperus pangorei*-derived carbon electrode recorded at different scan rates in the potential window of 0-1.5V using PVA / Na_2SO_4 gel polymer electrolyte are shown in Fig. 3. The CV curves exhibit a quasi-rectangular shape with distinct redox peaks, indicating that the charge-storage process involves both electric double-layer capacitance and pseudocapacitive contributions[15]. The presence of redox peaks may be attributed to the oxygen-containing functional groups present on the carbon surface, as confirmed by FTIR analysis.

With increasing scan rate, the current response increases while the overall shape of the CV curves is retained, indicating good rate capability and rapid charge transport within the electrode material. The deviation from an ideal rectangular shape suggests the occurrence of faradaic reactions associated with the surface functional groups, which contribute additional capacitance beyond the electric double-layer mechanism[16]. The specific capacitance was calculated using the following equation.

$$C_s = \frac{Q}{m\Delta V} \quad \ldots (1)$$

where C_s (F g^{-1}) is the specific capacitance, Q (C) is the average charge obtained from the anodic and cathodic scans, m (g) is the mass of the active material and ΔV (V) is the potential window. The specific capacitance values of the prepared carbon electrode were found to be 256, 355, and 476 F g^{-1} at scan rates of 100, 50, and 25 mV s^{-1}, respectively. The relatively high capacitance values obtained even at elevated scan rates indicate good rate capability and efficient charge transport within the electrode material. The PVA / Na_2SO_4 gel electrolyte provided stable electrochemical behaviour over the investigated potential window of 0-1.5 V. No significant increase in current associated with electrolyte decomposition or gas evolution was observed, indicating that the selected operating window was suitable for evaluating the electrochemical performance of the prepared carbon electrode.

Furthermore the specific capacitance of the present carbon electrode is higher than those reported for several biomass-derived carbons, as summarized in Table 1. The enhanced capacitive performance can be attributed to the combined contribution of electric double-layer capacitance and pseudocapacitance

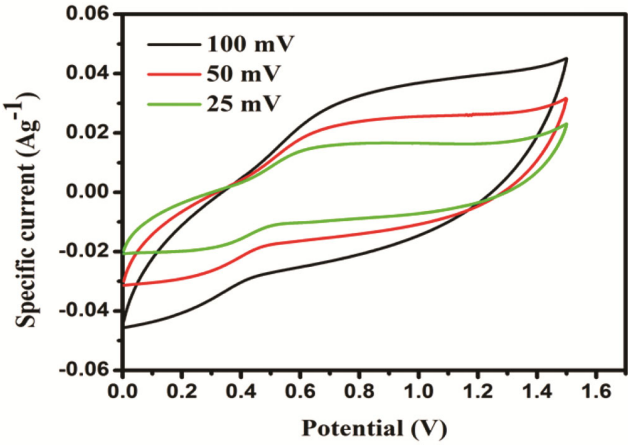

Fig. 3 — CV curves of the *Cyperus pangorei*-derived carbon electrode

Table 1 — Specific capacitance of the prepared carbon compared with other natural sources

Sample	Activation method	Specific capacitance (F g^{-1})	Electrolyte	References
Coffee beans	$ZnCl_2$	368 at 0.05 A g^{-1}	H_2SO_4	17
Coffee shells	$ZnCl_2$	156 at 1 mV s^{-1}	KOH	18
Cassava peel	KOH & CO_2	264 at 20 mV s^{-1}	H_2SO_4	19
Sugar cane bagasse	$ZnCl_2$	300 at 0.25 A g^{-1}	H_2SO_4	20
Sunflower seed shell	KOH	311 at 0.25 A g^{-1}	KOH	21
Cotton stalk	H_3PO_4	114 at 0.5 A g^{-1}	Et_4NBF_4	22
Coconut shell	KOH	156 at 2 mV s^{-1}	KOH	23
Rice husk	KOH	367 at 5 mV s^{-1}	KOH	24
Cyperus pangorei	Annealed	476 at 25 A g^{-1}	PVA with Na_2SO_4	Present work

arising from oxygen-containing surface functional groups. These functional groups improve the wettability of the electrode surface and facilitate reversible faradaic reactions, thereby contributing additional charge-storage capacity. Fig. 4 shows the variation of specific capacitance with scan rate. A gradual decrease in capacitance is observed with increasing scan rate. At higher scan rates, electrolyte ions have insufficient time to penetrate the inner pores and access all available electroactive sites, resulting in charge storage predominantly at the outer surface of the electrode. In contrast, at lower scan rates, the electrolyte ions can effectively diffuse into the porous structure and utilize a larger number of electroactive sites leading to enhanced charge storage and higher specific capacitance.

Charge-discharge studies

Fig. 5 shows the galvanostatic charge–discharge curves of the *Cyperus pangorei*-derived carbon electrode recorded at different current densities within a potential window of 0-1.5V. The charge-discharge profiles exhibit a nearly symmetric shape, indicating good reversibility and capacitive behaviour of the electrode material. A slight deviation from the ideal triangular shape is observed suggesting the coexistence of electric double-layer capacitance and pseudocapacitive charge-storage mechanisms. The pseudocapacitive contribution may arise from the oxygen-containing functional groups present on the carbon surface as evidenced by the FTIR analysis.

The specific capacitance (Cs) of the electrode was calculated from the discharge curves using the following equation[25]

$$C_s = \frac{i\Delta t}{m\Delta V} \quad \ldots (2)$$

Where C_s (F g^{-1}) is specific capacitance, i (A) is the current density, m (g) is the mass of the active material in the electrode, ΔV (V) is the potential window and Δt (s) is the discharge time. The estimated specific capacitance values of the electrodes in the present work are 476, 320, 240 and 200 F g^{-1} corresponding to the current densities of 25, 30, 40 and 50 A g^{-1}, respectively. The nearly symmetric charge–discharge curves and extended discharge times indicate efficient charge storage and good electrochemical reversibility. The enhanced capacitive performance can be attributed to the combined effect of electric double-layer formation and Faradaic reactions associated with the surface functional groups. These results further confirm the suitability of the prepared carbon material as a promising electrode for supercapacitor applications. Deviation of charge discharge curve from triangle shape is due to the functional groups attached to the surface of the carbon material. Fig. 6 shows the variation of specific capacitance as a function of specific currents. The decreasing trend of specific capacitance suggests that parts of the surface of the electrode are inaccessible at high-discharging rates. Hence the specific capacitance values obtained at low current densities may due to the closet to the full utilization of the electrode material.[26]

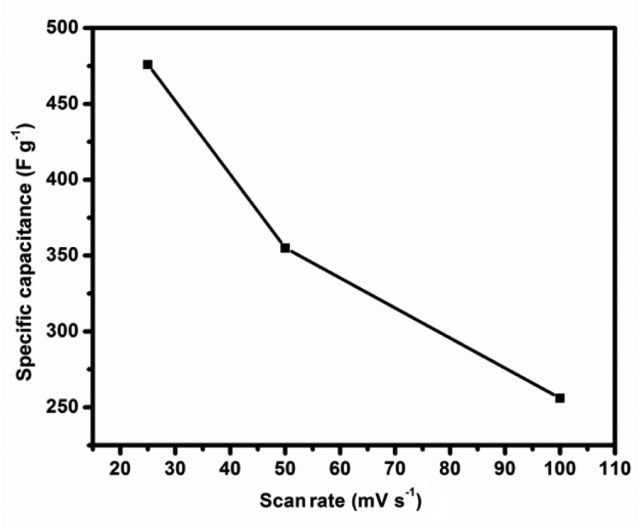

Fig. 4 — The change of specific capacitance with scan rate in *Cyperus pangorei*-derived carbon electrode

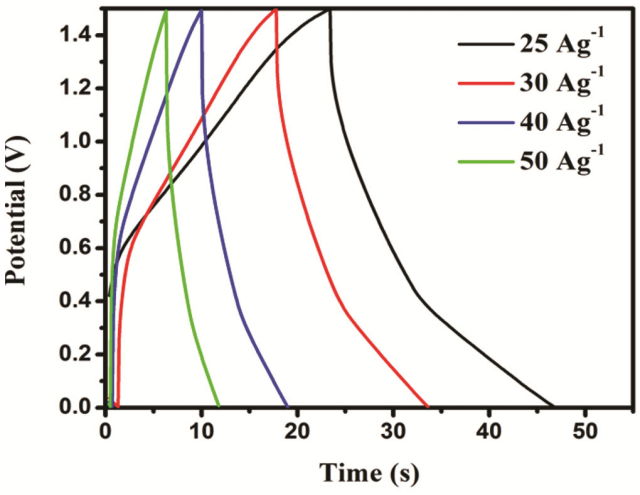

Fig. 5 — GCD curves of the *Cyperus pangorei*-derived carbon electrode

Electrochemical impedance spectroscopy

Electrochemical impedance spectroscopy was employed to evaluate the charge transport characteristics and ion diffusion behaviour of the *Cyperus pangorei*-derived carbon electrode. The impedance measurements were carried out over a frequency range of 0.01 Hz to 100 kHz and the corresponding Nyquist plot is shown in Fig. 7. In the high-frequency region, a small semicircle is observed which is associated with the charge-transfer resistance (R_{ct}) at the electrode–electrolyte interface. The diameter of the semicircle provides a measure of the charge-transfer resistance and the prepared carbon electrode exhibited a low (R_{ct}) value of 1.5 Ω. The low charge-transfer resistance indicates efficient electron transport and favourable electrochemical kinetics at the electrode surface. In the low-frequency region, the Nyquist plot exhibits an inclined straight line characteristic of Warburg impedance, which is related to the diffusion of electrolyte ions within the porous electrode structure[26]. The presence of this feature suggests effective ion transport and electrolyte accessibility throughout the electrode material. The low charge-transfer resistance and favourable ion diffusion characteristics demonstrate the excellent electrochemical conductivity of the prepared carbon electrode. This reduced interfacial resistance can be attributed to the highly porous carbon structure and the presence of surface functional groups, which facilitate electrolyte penetration and provide abundant active sites for ion adsorption. Furthermore, the low impedance behaviour promotes rapid ion diffusion and minimizes energy losses during charge-discharge processes, contributing to the enhanced specific capacitance and superior rate capability of the electrode. These results are consistent with the high specific capacitance obtained from cyclic voltammetry and galvanostatic charge-discharge measurements. Therefore, the EIS analysis confirms that the *Cyperus pangorei*-derived carbon is a promising electrode material for supercapacitor applications.

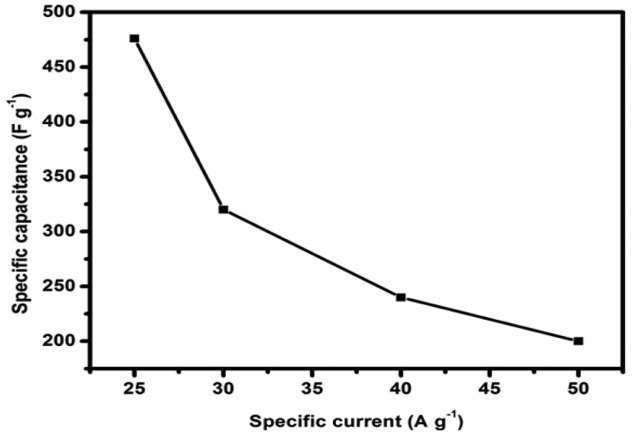

Fig. 6 — The change of specific capacitance with specific current in *Cyperus pangorei*-derived carbon electrode

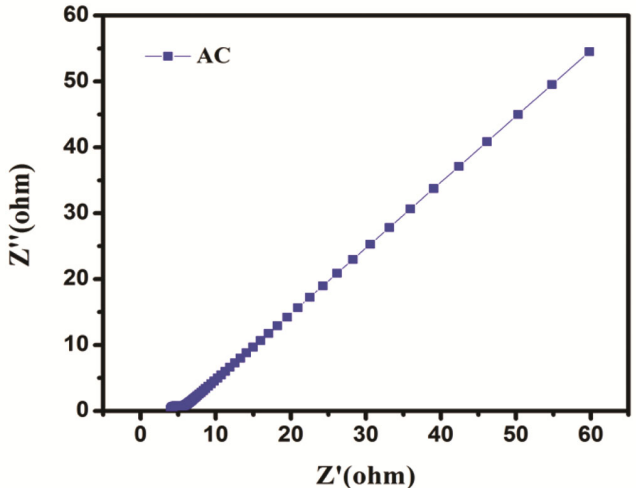

Fig. 7 — Nyquist plot of the *Cyperus pangorei*-derived carbon electrode

Cycling stability is an important parameter for assessing the practical applicability of supercapacitor electrode materials. The cycling performance of the *Cyperus pangorei*-derived carbon electrode was evaluated through repeated galvanostatic charge-discharge measurements at a current density of 50 A g^{-1}. The corresponding cycling stability profile is presented in Fig. 8. During the initial stage of cycling, the specific capacitance increased from 154 F g^{-1} to 168 F g^{-1} within the first 20 cycles, corresponding to a capacitance enhancement of approximately 9%. This

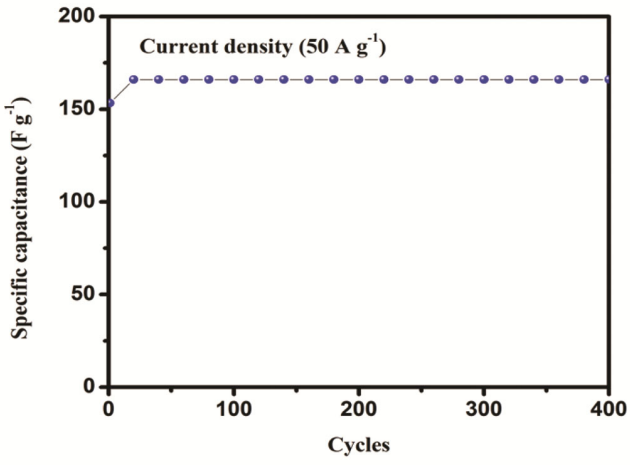

Fig. 8 — Cyclic stability of the *Cyperus pangorei*-derived carbon electrode

increase may be attributed to the gradual activation of the electrode surface and improved penetration of electrolyte ions into the accessible pores of the carbon material. Such activation behavior is commonly observed in porous carbon electrodes during the initial charge-discharge cycles. Beyond the initial activation stage, the capacitance remained nearly constant from the 20^{th} cycle up to 400 continuous charge-discharge cycles, indicating excellent electrochemical stability and reversibility of the electrode material. The negligible capacitance loss observed during prolonged cycling demonstrates the structural stability of the carbon electrode and its ability to sustain repeated charge-storage processes without significant degradation. The combination of high specific capacitance, good rate capability, low charge-transfer resistance and excellent cycling stability highlights the potential of *Cyperus pangorei*-derived carbon as a promising electrode material for electrochemical double-layer capacitors and related energy storage applications.

Conclusion

The biomass derived carbon was obtained from natural grass through thermal decomposition method. Through charge-discharge measurements, a maximum specific capacitance of 476 F g^{-1} was obtained at a current density of 25 A g^{-1}. The values obtained through CV are also of the same order. The low charge transfer resistance combined with the high capacity results demonstrates that *Cyperus pangorei*-derived carbon is a promising low-cost and sustainable electrode material for supercapacitor applications. The present work further supports the growing interest in sustainable biomass-derived carbon electrodes for electrochemical energy storage and aligns with recent developments in this rapidly evolving research area.

Conflict of Interest

The authors declare no conflict of interest.

Supplementary Information

Supplementary information is available on the website https://nopr.niscpr.res.in/handle/123456789.

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