

Influence of Chemical Activation on the Structural and Electrochemical Properties of *Calophyllum inophyllum* Shell-Derived Porous Carbon for Supercapacitor Application

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Abstract

Biomass-derived porous carbons are effective electrode materials for supercapacitors due to their variable porosity, substantial surface area, and environmental sustainability. In this work, activated porous carbons were created from *Calophyllum inophyllum* shell waste through carbonization and chemical activation using NaOH, H₂SO₄, and H₃PO₄. The structural, surface, and electrochemical characteristics of the produced samples were methodically examined in relation to the impact of activation chemistry. The NaOH-activated carbon had the highest specific capacitance of 638.21 F g⁻¹ at 10 mVs⁻¹ among the produced samples, indicating improved electrolyte ion accessibility and effective charge transport behavior. With a specific capacitance of 59.06 F g⁻¹ and an energy density of 4.02 Wh kg⁻¹, galvanostatic charge–discharge analysis revealed that the H₂SO₄-activated carbon provided the best overall performance, underscoring the significance of balanced pore architecture for useful charge storage. The development of interconnected hierarchical porous structures and increased electrochemically accessible surface area following alkaline activation are responsible for the improved performance. According to comparative analysis, activation chemistry is essential for customizing the pore architecture, surface functionality, and charge-storage properties of carbons generated from biomass. The present study demonstrates that *Calophyllum inophyllum* shell waste is a promising sustainable precursor for the development of high-performance porous carbon electrode materials for next-generation supercapacitor applications.

1. Introduction

The rapid increase in global energy demand and the growing dependence on renewable energy technologies have intensified the need for efficient energy storage systems^{1–4}. Among various energy storage devices^{5–7}, super capacitors have received much attention due to the fact that they have high-power density⁸, rapid charge–discharge capability⁹, excellent cycling stability¹⁰ and superior reversibility¹¹. However, the development of sustainable, low-cost, and high-performance electrode materials remains a major challenge for advanced supercapacitor applications.

Biomass-derived activated carbons (BDAC) have emerged as promising electrode materials due to their renewable nature^{12,13}, tunable pore size¹⁴, high surface area¹⁵, and environmentally sustainable¹⁶. In particular, porous carbon materials generated through chemical activation provide interconnected ion-transport pathways¹⁷ and enhanced electrochemically accessible surface area¹⁸, which are highly beneficial for electric double-layer capacitive (EDLC)¹⁹ performance. Various biomass precursors such as coconut shell (215.77 m²g⁻¹)²⁰, rice husk (307.42 m²g⁻¹)²¹, coffee waste (between 585 and 2330 m²g⁻¹)²², banana peel area (218.339 m²g⁻¹)²³, tamarind seed²⁴ and agricultural residues^{25–27} have been explored for porous carbon production in supercapacitor applications.

Despite extensive studies on biomass-derived porous carbons, the electrochemical potential of *Calophyllum inophyllum* shell waste remains largely unexplored. *Calophyllum inophyllum* is abundantly available in tropical coastal regions of South India and generates significant shell waste during bio-oil^{28,29} and biodiesel^{30,31} processing. The shell contains high lignin and fixed-carbon content, making it a promising precursor for the formation of stable microporous carbon frameworks after activation. However, systematic investigations correlating activation chemistry, pore development, and electrochemical performance of *Calophyllum inophyllum*-derived activated carbons are limited.

The surface area, pore structure, conductivity, and electrolyte accessibility of biomass-derived carbons can all be tailored through chemical activation. Pore-generation mechanisms and carbonization behavior are influenced differentially by different activating agents. Acid activation using H₂SO₄ (487.5 Fg⁻¹ specific capacitance at 1 Ag⁻¹)³² and H₃PO₄³³ specific surface areas (from 1200 m²g⁻¹ to 1880 m²g⁻¹) at 500°C promotes dehydration and surface oxidation, whereas alkaline activation using NaOH facilitates extensive pore etching and micropore development with increasing elemental composition 90.99% of carbon presence³⁴. Therefore, a comparative investigation of different activation strategies is essential to optimize the electrochemical properties of biomass-derived porous carbons for supercapacitor applications.

Calophyllum inophyllum shell waste has attracted interest as a sustainable biomass resource for the production of activated carbon and other value-added applications. However, to act as an excellent precursor for activated carbon electrodes for energy storage by electrochemistry remains largely unexplored. In the present study, porous activated carbons were synthesized from *Calophyllum inophyllum* shell waste through carbonization followed by chemical activation using NaOH, H₂SO₄, and H₃PO₄ has been reported for the first time for energy storage application. The influence of activation chemistry on the structure, morphology, surface, and electrochemical properties of the prepared carbons was systematically investigated using XRD, SEM, FTIR, Raman spectroscopy, BET surface area analysis, and electrochemical techniques including CV, GCD, and EIS. The results demonstrate the significant role of activation chemistry in engineering highly porous carbon frameworks for high-performance supercapacitor applications. As far as we know, this is the first systematic evaluation of activation methods of NaOH, H₂SO₄, and H₃PO₄ for *Calophyllum inophyllum* shell-derived porous carbon electrodes for supercapacitor applications.

2. Experimental Section

2.1 Materials

The *Calophyllum inophyllum* shell biomass was collected from the naturally growing trees in the Kanyakumari District, Tamil Nadu, India, and used as the precursor material for activated carbon synthesis. All reagents were of analytical grade and were used as purchased. Sodium Hydroxide (NaOH), Sulfuric Acid (H₂SO₄), Phosphoric Acid (H₃PO₄), Ethanol (C₂H₅OH), Polyvinylidene fluoride (PVDF, -(C₂H₂F₂) n-), Acetylene Black (AB), and N-methyl-2-pyrrolidone (NMP, C₅H₉NO) were purchased from Sigma-Aldrich.

2.2 Synthesis of Biomass-derived Carbon (BDC)

Mature *Calophyllum inophyllum* shells collected from natural source were utilized to extract the carbon precursor. Subsequent to collection, the shell was cleansed and left to desiccate in sunlight for 48 hours. This simplifies the filtration and separation procedures. The process of filtration involves removing the seeds from the centre of the fruit. When the seed is extracted, the outer and inner layers of the shell separate, leaving only the shell for the second stage. After the shell is obtained, it is subjected to a 30-minute sonication procedure. Because the residue will remain as ash throughout the charring process, this procedure is used to remove dirt and residue from the shell. The shell is incinerated in the furnace for 2 hours at 500°C, increasing by 10 degrees every minute. After 2 hours, a substantial quantity of *Calophyllum inophyllum* charcoal was generated. To produce fine carbon powder, the resulting char was pulverized using a pestle and mortar and subsequently sifted through an ASTM No. 200 (~ 75 µm) screen. At this stage, the powdered bio-mass derived carbon (BDC) was primed for activation coded as CA-1.

2.2 Preparation of activated carbon

The activation process is carried out by chemical activation. Three activating compounds, specifically NaOH, H₂SO₄, and H₃PO₄, which are analytical grade, were utilized for the activation processes. For each activation experiment, 3 g of carbon was accurately weighed using an analytical balance. Based on previous literature, carbon-to-activating agent weight ratios of 1:1.5 and 1:2 were selected to investigate the effect of activation conditions. **Fig.S1** illustrates the schematic representation of the prepared BDAC. The sample is immersed in the activation agent for 24 hours. Upon activation, the sample is then subjected to carbonization at a furnace temperature of 500°C at a rate of 10°C/min for 2 hours. The activated carbon is subsequently rinsed with HCl and distilled water until achieving a pH of 7–8 for neutralization. The washed sample is then dried under vacuum at 100°C for 24 hours. The different types of the activated carbon samples obtained were referred to as CA-2 and CA-3 (NaOH), CA-4 and CA-5 (H₂SO₄), and CA-6 and CA-7 (H₃PO₄). The activated carbon is prepared for synthesis and thereafter sent for BET, FESEM, and XRD studies to ascertain pore size and structure.

2.3 Electrochemical measurement

The electrochemical properties of the synthesized electrode were investigated using three-electrode cell connected to a potential system under room temperature conditions. Herein, Ag/AgCl was considered as the reference electrode, Pt spring as the counter electrode, and the working electrode was synthesized by depositing the sample on graphite foil. The electrode slurry was made by dispersing the sample, AB and PVDF binder with the ratio of 8:1:1 in NMP solution to get a homogeneous mixture and this electrode slurry is applied onto graphite foil. A 1 M aqueous KOH solution was used as an electrolyte. The CV, GCD, and EIS experiments were conducted within the voltage range of – 0.2 V to 0.5 V. The specific capacitance from CV and GCD curves were determined through the Eq. 1 and Eq. 2, respectively. The energy density and power density were calculated using Eq. 3 and Eq. 4, respectively as follows^{35–38} :

$$C_s = \frac{1}{(2mv\Delta v)} \int I(V) dV \quad (\text{Fg}^{-1})$$

$$C_s = \frac{(I\Delta t)}{(m\Delta v)} \quad (\text{Fg}^{-1})$$

$$E_d = \frac{(C_s \times V^2 V)}{(2 \times 3.6)} \quad (\text{Wh kg}^{-1})$$

$$P_d = \frac{(E_d \times 3600)}{\Delta t} \quad (\text{W kg}^{-1})$$

where C_s represents the specific capacitance (F g^{-1}), m is the mass of the active material (g), $\int I(V) dV$ is the integrated area under the CV curve, v is the scan rate (V s^{-1}), ΔV is the potential window, I is the applied current (A), and Δt is the discharge time (s). E_d and P_d are the energy density (Wh kg^{-1}) and power density (W kg^{-1}).

3. Results and Discussion

3.1 Structural and morphological analysis

3.1.1 X-Ray Diffraction (XRD)

The purity and structure of BDC and BDAC activated by chemical activation were analyzed using X-ray diffractometer (XRD, D8 Advance DAVINCI, Bruker AXS, USA). From Fig. S2, it can be seen that these materials show wide peaks at $2\theta = 23^\circ$ and 44° , which represent the (002) and (100) planes of graphitic carbon (JCP No. 00-056-0159)³⁵, indicating predominantly amorphous carbon structures with partial graphitic ordering. Compared with BDC, the activated samples showed a gradual shift in the (002) peak toward higher 2θ values and a reduction in d-spacing from 3.93 to 3.83 Å, confirming improved carbon layer

stacking after activation. Furthermore, the decrease in FWHM values and increase in crystallite size from 1.74 to 2.01 nm indicate improved structural ordering in the activated carbons. Among the activated samples, H_3PO_4 -treated carbons (BDAC-CA-6 and BDAC-CA-7) exhibited relatively improved graphitic ordering, whereas NaOH- and H_2SO_4 -activated samples showed comparatively higher structural disorder and porous framework development.

3.1.2 Scanning Electron Microscope (SEM)

Surface morphologies of the synthesized carbon materials were characterized by TESCAN VEGA3 scanning electron microscope. As shown in Fig. 1a), the raw carbon (CA-1) exhibited irregular flake-like carbon morphology with limited visible porosity, indicating a relatively dense carbon framework prior to activation³⁹. Depending on the activating agent, notable morphological alterations were seen upon chemical activation (Fig. 1b-g). Effective pore creation during alkaline activation was demonstrated by the NaOH-activated carbons' significant surface etching and linked porous structures. The H_2SO_4 -activated samples, on the other hand, maintained somewhat smoother flake-like morphologies with mild pore formation, indicating regulated surface change after acid treatment. Meanwhile, the H_3PO_4 -activated carbons exhibited more uniformly distributed porous structures and well-developed porous features, indicating enhanced pore formation after phosphoric acid activation. The enhanced porous morphology observed in the activated carbons is consistent with the BET results, which demonstrated increased nitrogen adsorption uptake and improved surface accessibility following chemical activation. Furthermore, the structural disorder and defect-rich carbon framework observed from the Raman spectra, together with the oxygen-containing surface functionalities confirmed by XPS analysis, further support the successful surface modification and pore development after chemical activation. The development of interconnected porous structures is expected to facilitate electrolyte ion diffusion and improve electrochemical charge storage performance.

EDX analysis confirmed that carbon and oxygen were the predominant elements in all samples, indicating the successful formation of biomass-derived porous carbon materials. Among all samples as shown in Fig. S3, the NaOH-activated carbon exhibited the highest atomic carbon percentage (~ 87%), indicating enhanced purification and development of a carbon-rich framework after alkaline activation. In contrast, H_2SO_4 -activated carbons showed relatively higher oxygen content, suggesting the incorporation of oxygen-containing surface functionalities through acid treatment. Furthermore, the H_3PO_4 -activated carbons additionally exhibited the presence of phosphorus species, indicating successful phosphorus-assisted surface modification during activation. Notably, the carbon content achieved for the NaOH-activated carbon in the present study exceeds that reported for H_2SO_4 -activated biomass-derived carbon in a previous study⁴⁰, demonstrating the superior effectiveness of NaOH activation in promoting carbon enrichment.

3.1.3 Fourier Transform Infrared Spectroscopy (FTIR)

Using Fourier transform infrared (FTIR) spectroscopy (PTS-2-QE, Science Tech Inc., Canada) in the wavenumber range of 4000–400 cm^{-1} , the surface functional groups of the produced carbon samples were examined. The raw biomass-derived carbon's FTIR spectra showed a wide absorption band centred at around 3400 cm^{-1} , which corresponded to O–H stretching vibrations linked to adsorbed moisture and surface hydroxyl groups. The creation of carbonaceous structures during carbonization was confirmed by the band about ~ 1600 cm^{-1} , which corresponded to aromatic skeletal C = C vibrations, and the absorption peak near ~ 2920 cm^{-1} , which was attributable to aliphatic C–H stretching vibrations. Additional peaks at ~ 1380 cm^{-1} and ~ 1050–1100 cm^{-1} were attributed to C–H bending and C–O stretching vibrations, respectively, which are typical of porous carbons generated from biomass.

The chemically activated carbons showed differences in peak intensity and band broadening when compared to the raw carbon as seen in Fig. 2, suggesting surface alteration following activation treatment. The C = C and C–O bands were comparatively elevated in the NaOH-activated carbons, indicating increased aromatic character and the formation of oxygen-containing surface functions during alkaline activation. The H_2SO_4 -activated carbons, on the other hand, showed stronger C–O stretching characteristics and wider O–H absorption bands, suggesting greater surface oxidation brought on by acid treatment. Additionally, across the 1000–1200 cm^{-1} area, the H_3PO_4 -activated carbons showed relatively greater absorption. This could be related to phosphate-linked oxygen functions and improved surface modification following phosphoric acid activation. The inclusion of oxygen-containing functional groups is expected to improve electrolyte wettability and ion accessibility inside the porous carbon framework, which will be advantageous for electrochemical energy storage applications. Chemical activation considerably altered the surface chemistry and porous properties of the carbon materials, as confirmed by the FTIR data, which agree with the SEM and BET investigations.

3.1.4 Raman Spectroscopy

Using a Laser Confocal Raman Microscope (in Via Raman, Renishaw, UK), Raman spectroscopy was used to examine the structural disorder and graphitic properties of the carbon materials. All samples had two distinctive peaks at around 1350 cm^{-1} and about 1590–1605 cm^{-1} , which correspond to the D and G bands, respectively, as seen in Fig. 3. While the G band represents the stretching of sp^2 -hybridized graphitic carbon networks, the D band is linked to structural flaws and disordered carbon domains⁴¹. Similar levels of structural disorder and partial graphitization within the carbon framework are indicated by the comparable (I_D/I_G) ratios found for the chemically activated and raw carbons. The highest (I_D/I_G) value of 0.858 among the activated samples indicates comparatively higher surface disorder and defect density brought on by chemical activation. Overall, the Raman data show that the activation method mostly affected pore formation and surface modification while maintaining the carbon matrix's inherent graphitic structure, which is beneficial for electrochemical energy storage applications.

3.1.5 X-Ray photoelectron spectroscopy

The produced carbon materials' surface elemental composition and chemical bonding states were examined using X-ray photoelectron spectroscopy (XPS) and a Thermo Scientific K-Alpha X-ray Photoelectron Spectrometer (Thermo Fisher Scientific, USA). Following chemical activation, the existence of carbon (C 1s) and oxygen (O 1s) was confirmed by the XPS spectra shown in Fig. S4. The characteristic peaks at ~ 284.5, ~ 286, and ~ 288–289 eV in the high-resolution C 1s spectra corresponded to sp^2 -hybridized C–C/C = C, C–O/C–OH, and O–C = O functional groups, respectively. In addition, the O 1s spectra

displayed peaks centred at $\sim 531\text{--}532\text{ eV}$ and $\sim 533\text{--}534\text{ eV}$, attributed to $\text{C}=\text{O}$ and C-O/C-OH oxygen species. Compared with the raw biomass-derived carbon (CA-1), the chemically activated carbons exhibited enhanced surface functionalization and modified carbon chemistry. The NaOH -activated carbons (CA-2 and CA-3) showed relatively stronger sp^2 carbon contributions, indicating improved graphitic character after alkaline activation, whereas the H_2SO_4 -activated carbons (CA-4 and CA-5) exhibited comparatively intensified oxygen-related peaks due to increased surface oxidation. Furthermore, the H_3PO_4 -activated carbons (CA-6 and CA-7) demonstrated enhanced surface modification associated with phosphorus-assisted activation. The XPS results are consistent with the FTIR and EDX analyses, confirming effective chemical activation and surface modification of the biomass-derived porous carbon materials.

3.1.6 BET Analysis

In order to examine the surface area and porosity of the obtained raw and chemically activated carbon materials, BET method was applied using a N_2 adsorption/desorption analyzer. According to the results, the adsorption-desorption isotherms were characterized by micro-mesoporous nature similar to Type IV isotherms⁴². Thus, the development of porous structure of carbon materials due to chemical activation was achieved successfully as shown in Fig. 4. BET textural parameters, such as specific surface area, total pore volume and average pore diameter of all obtained carbon samples are given in Table S1. For the raw carbon material (CA-1), surface area was found to be $331.515\text{ m}^2\text{g}^{-1}$ with pore volume of 0.539 cc g^{-1} and average pore size of 1.54 nm . With the application of chemical activation process, considerable differences were observed in terms of textural parameters depending on the activating agent. The NaOH -activated carbon samples (CA-2 and CA-3) have specific surface areas of 328.823 and $225.250\text{ m}^2\text{g}^{-1}$, pore volumes of 0.151 and 0.426 cc g^{-1} and pore diameter of 1.68 and 1.55 nm , indicating moderate pore development during alkaline activation. In contrast, the H_2SO_4 -activated carbons (CA-4 and CA-5) displayed comparatively higher surface areas of 588.993 and $609.700\text{ m}^2\text{g}^{-1}$, with corresponding pore volume of 0.235 and 0.249 cc g^{-1} with a pore diameter of 1.23 and 1.23 nm respectively, confirming enhanced pore generation upon sulfuric acid activation. Among all the samples H_3PO_4 -activated carbons demonstrated superior porosity characteristics. CA-6 with a surface area of $479.753\text{ m}^2\text{g}^{-1}$ with a pore volume of 0.214 cc g^{-1} and a pore size of 1.23 nm , while CA-7 exhibiting the highest surface area of $1014.742\text{ m}^2\text{g}^{-1}$ three times greater than that of the raw carbon with a pore volume of 0.417 cc g^{-1} with a pore size of 1.23 nm , indicating the formation of a highly porous structure. Although CA-7 exhibited the highest BET surface area, electrochemical properties are not only determined by the surface area but also by pore-size distribution and ion transport pathways. Excessive microporosity may limit electrolyte diffusion, whereas a balanced micro-mesoporous structure facilitates efficient electrolyte accessibility and charge storage. This may explain the superior electrochemical performance observed for CA-2 and CA-5 despite their lower surface areas. The enhanced pore structure and increased surface accessibility generated after chemical activation are consistent with the SEM observations and are expected to improve the electrode-electrolyte interface and facilitate efficient electrolyte ion transport, thereby contributing to enhanced electrochemical charge storage performance.

3.1.7 Electrochemical Analysis

The electrochemical performance of the prepared biomass-derived porous carbon electrodes was systematically evaluated using cyclic voltammetry (CV), Galvanostatic charge-discharge (GCD), and Electrochemical impedance spectroscopy (EIS) in a three-electrode configuration. All electrodes displayed quasi-rectangular CV profiles without clear redox peaks, as seen in Fig. 5, indicating dominant electric double-layer capacitive (EDLC) behavior with a small pseudocapacitive contribution resulting from oxygen-containing surface functionalities found by FTIR and XPS analyses. With a specific capacitance of 302.36 F g^{-1} at 10 mV s^{-1} and 247.79 F g^{-1} at 100 mV s^{-1} , the raw biomass-derived carbon (CA-1) showed the smallest enclosed CV area and the lowest current responsiveness. Because of its comparatively dense carbon framework, restricted pore accessibility, and less electrochemically active surface area before chemical activation, CA-1 exhibits poorer electrochemical behavior.

When compared to CA-1, all carbon electrodes showed noticeably improved electrochemical performance after activation. With significantly bigger enclosed areas and greater current responses than the raw carbon, the NaOH -activated series (CA-2 and CA-3) demonstrated the most improvement in CV properties. CA-2 produced the greatest CV-derived specific capacitance of 638.21 F g^{-1} at 10 mV s^{-1} of all the samples examined. NaOH activation's highly efficient pore-forming capacity, which encourages the formation of linked micro-mesoporous structures and greatly expands the electrochemically accessible surface area, is responsible for this amazing improvement. The BET results, which showed increased porosity and surface accessibility, and the Raman study, which showed improved graphitic ordering and electrical conductivity, are in good agreement with the superior capacitive behavior of CA-2. The positive impact of chemical activation on charge-storage performance is demonstrated by CA-5 (474.99 F g^{-1}), CA-4 (334.20 F g^{-1}), and CA-7 (310.35 F g^{-1}). Because of limited ion transport in micropores and decreased active site use at higher sweep rates, capacitance decreased in all samples as scan rate increased. The increased electrolyte accessibility and quicker ion transport made possible by the porous structure are indicated by the activated carbons' improved rate capacity. H_3PO_4 -activated samples (CA-6 and CA-7) outperformed CA-1, demonstrating successful activation by surface alteration and pore formation driven by phosphorus. In general, a hierarchical pore network rather than only surface area controls the electrochemical behavior, which is in line with BET and SEM findings⁴³.

Nearly symmetric triangular charge-discharge patterns with a modest IR drop were found by GCD analysis, suggesting mostly capacitive behavior and good reversibility. The pure CA-1 electrode produced a specific capacitance of 30.65 F g^{-1} at 0.5 A g^{-1} , along with energy and power densities of 2.09 Wh kg^{-1} and 175.34 W kg^{-1} , respectively. The charge-storage behavior was altered by chemical activation; CA-5 had the highest GCD-derived capacitance (59.06 F g^{-1}), followed by CA-4 (56.44 F g^{-1}), CA-6 (47.58 F g^{-1}), CA-7 (43.03 F g^{-1}), CA-2 (33.71 F g^{-1}), and CA-3 (28.99 F g^{-1}). The improved pore accessibility and surface functionality brought about by H_2SO_4 activation, which facilitates electrolyte-ion access to electrochemically active areas, may be linked to CA-5's better performance. The active electrodes' comparatively modest IR drop suggests decreased

The active electrodes' comparatively low IR drop suggests lower internal resistance, which is in line with better electrode-electrolyte interaction. The impact of activation on interfacial resistance and ion transport in the porous carbon network is further supported by the EIS response. These electrochemical properties align with the surface and structural alterations found by BET, SEM, Raman, FTIR, EDX, and XPS analyses.

Interestingly, different capacitance trends were seen in the GCD and CV tests. While CA-2 attained the largest CV-derived capacitance (638.21 F g⁻¹), CA-5 showed the highest GCD-derived capacitance. This variation suggests that under various electrochemical conditions, activation chemistry affects the equilibrium between accessible surface area, pore architecture, surface functionality, and ion transport. Overall, the findings show that chemical activation significantly modifies the electrochemical response of carbon produced from *C. inophyllum* shells, with different charge-storage properties resulting from NaOH and H₂SO₄ activation.

4. Conclusion

Through carbonization and chemical activation with NaOH, H₂SO₄, and H₃PO₄, porous activated carbons were successfully created from *Calophyllum inophyllum* shell waste. Activation chemistry had a major impact on pore architecture, surface properties, and electrochemical behaviour. While the H₂SO₄-activated carbon provided better GCD performance and energy density, the NaOH-activated carbon showed the highest CV-derived capacitance (638.21 F g⁻¹) among the examined samples. The findings show that optimal pore architecture and ion transport, not just surface area, control electrochemical performance. This work offers important insights into activation-controlled pore engineering for enhanced supercapacitor applications and emphasizes the potential of *Calophyllum inophyllum* shell waste as a sustainable precursor for high-performance porous carbon electrodes.

Declarations

Declaration of Competing Interest

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

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Author Contribution

CRediT authorship contribution statement Catherine.V : Investigation, Writing – original draft, Methodology, Conceptualization, Writing – review & editing. A.V. Jhone Verjhula: Supervision, Methodology, Review & editing.

Data Availability

All data and materials used in this research are available from the corresponding author upon reasonable request.

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Table

Table 1. Comparative analysis of this work with existing previous work from literatures

S. No.	Source material	Elemental analysis of C in %	Ratio	Activating agent and temperature	Structural Analysis		Chemical and Surface Analysis				Electrochemical Analysis		
					(XRD- study)		XPS		RAMAN (I _D /I _G)	BET (m ² /g)	Electrolyte	Scan rate/ current density (A/g)	Speci capac (F/g)
					2 (°)	Plane	C 1s (eV)	O 1s (eV)					
1.	Wood apple shell	76.41	1:1	H ₂ SO ₄ at 400 °C	25.46° 43.4°	(002) (100)	285.05	531.44 and 533.40	-	590	2M KOH	10	100
2.	Date seed	83.8	-	H ₂ SO ₄ at 700 °C	~23° ~43°	(002) (100)	-	-	0.83	-	1M KOH	1	487.5
3.	Cow Dung	-	4:1	H ₃ PO ₄ at 900 °C	26° 43°	(002) (101)	-	-	-	2457	6M KOH	10	305
4.	wood-dust	-	1:1	H ₃ PO ₄ at 400 °C	~26° ~ 30°	(002) (002)	-	-	~1	1269.5	6M KOH	1	136.3
5.	Chestnut shell	68.89	1:3	NaOH at 700 °C	~25° ~ 35°	- -	-	-	~1	768	6M KOH	1	625
7.	Rice husk	-	4:1	NaOH at 700 °C	~ 30° 43°	(002) -	285.39	532.46	-	307.42	6M KOH	0.5	112
8.	Date palm fronds	-	1:4	NaOH at 700 °C	-	-	285.48	-	~1	1011	1M H ₂ SO ₄	20	55.9
9.	<i>Calophyllum inophyllum</i> shell	84.08	1:1.5	NaOH at 500 °C	23°	(002)	~286	~533	~1	328.823	1M KOH	10	638.2
		87.00	1:2		44°	(100)				225.250			310.3
		78.70								588.993			334.2
			1:1.5	H ₂ SO ₄ at 500°C							1M KOH		
		68.53	1:2							609.700			474.9
		80.70	1:1.5							479.753			389.3
		73.11	1:2	H ₃ PO ₄ at 500°C						1014.742			474.9

Figures

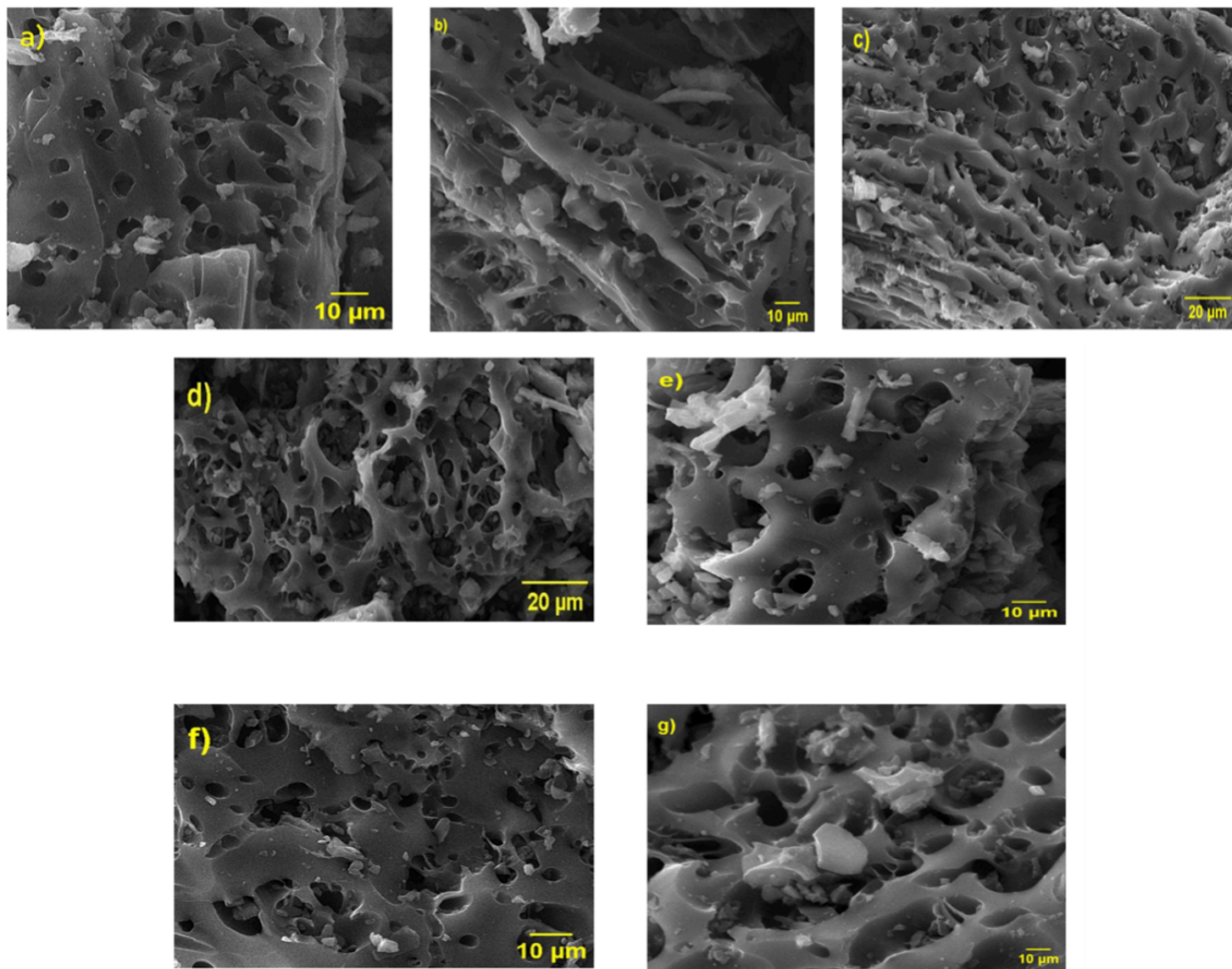


Figure 1

Morphological analysis of the samples a) CA-1 b) CA-2 c) CA-3 d) CA-4 e) CA-5 f) CA-6 g) CA-7

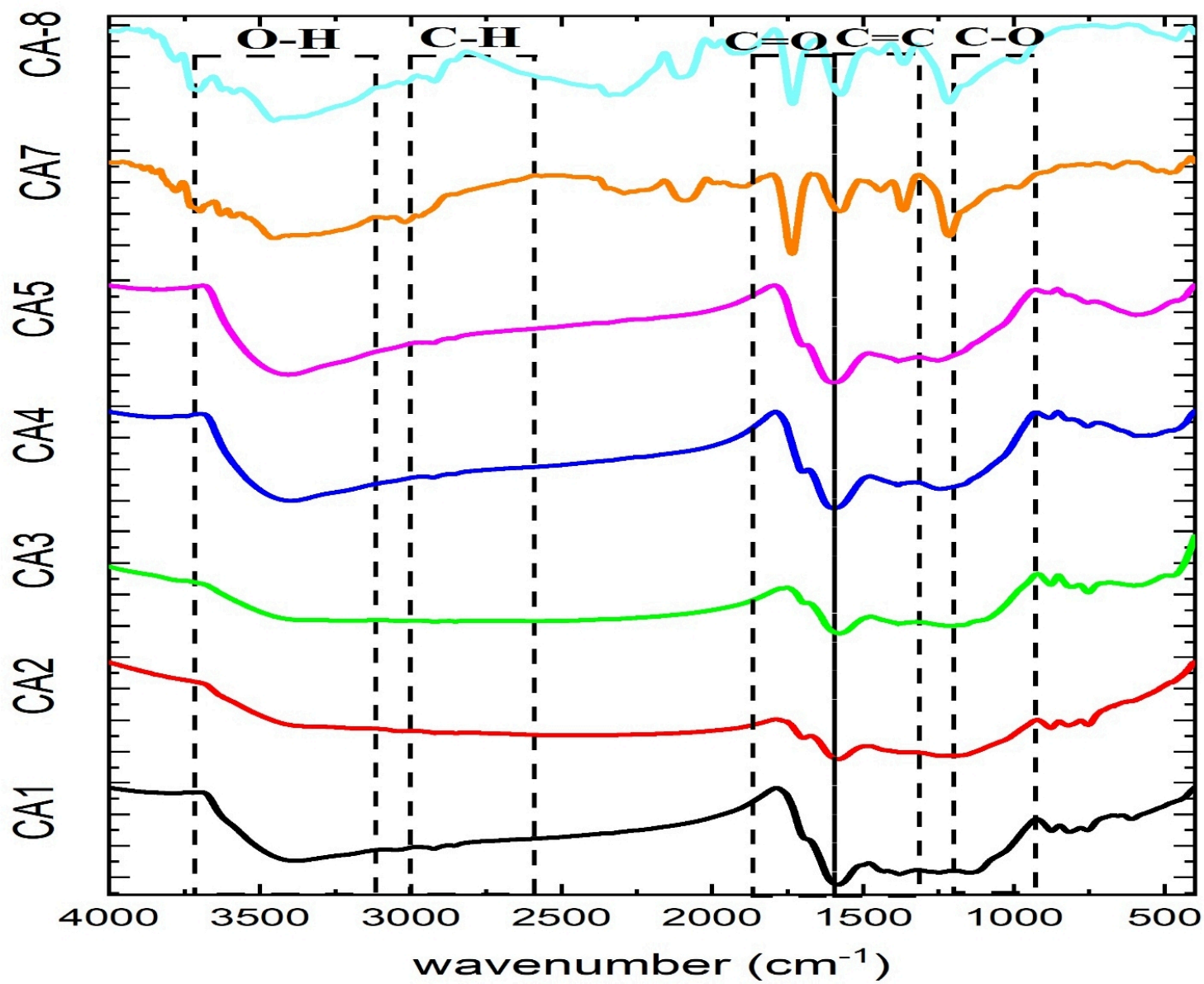


Figure 2

FTIR analysis of BDC and BDAC

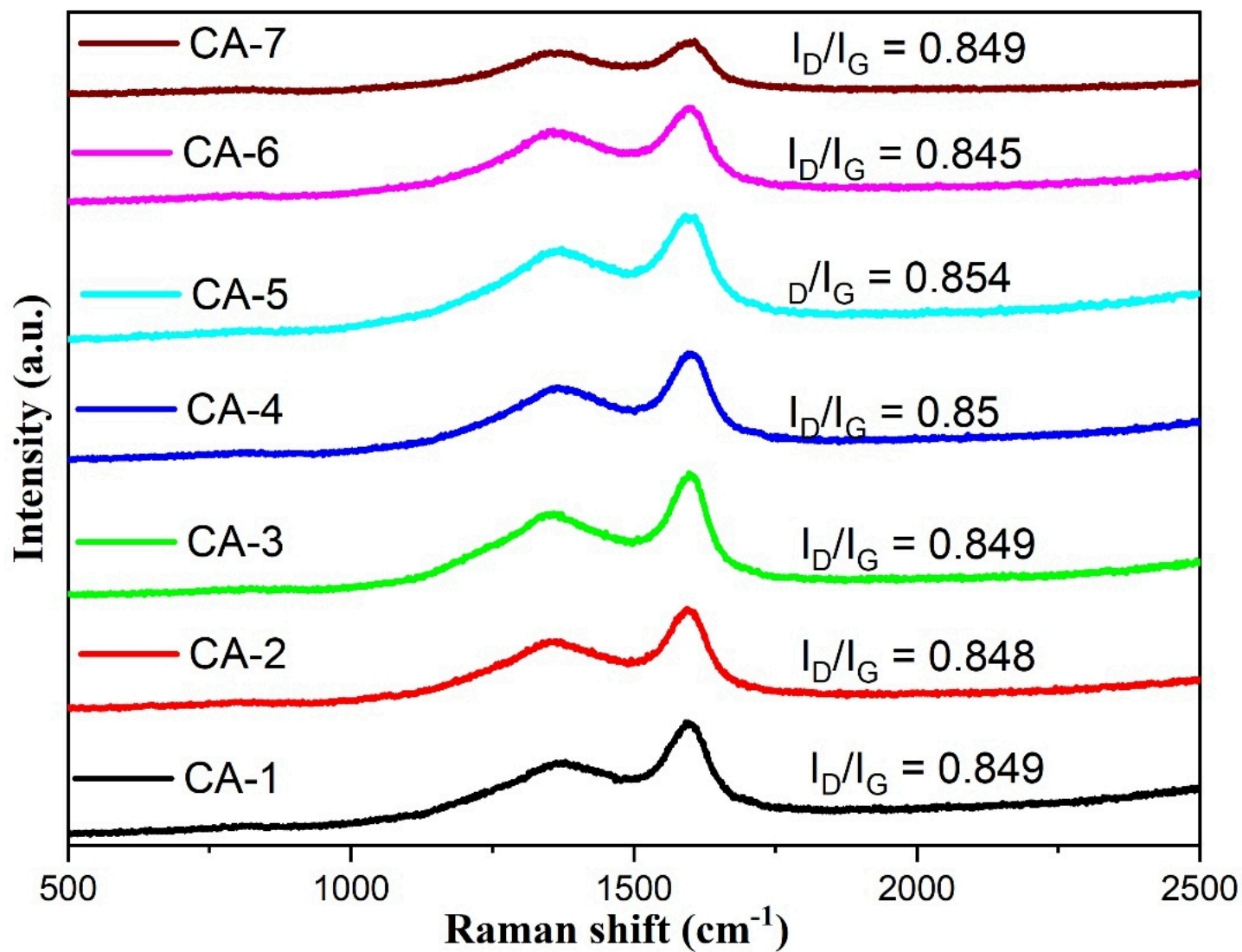


Figure 3

Raman Spectra of CA-1 to CA-8

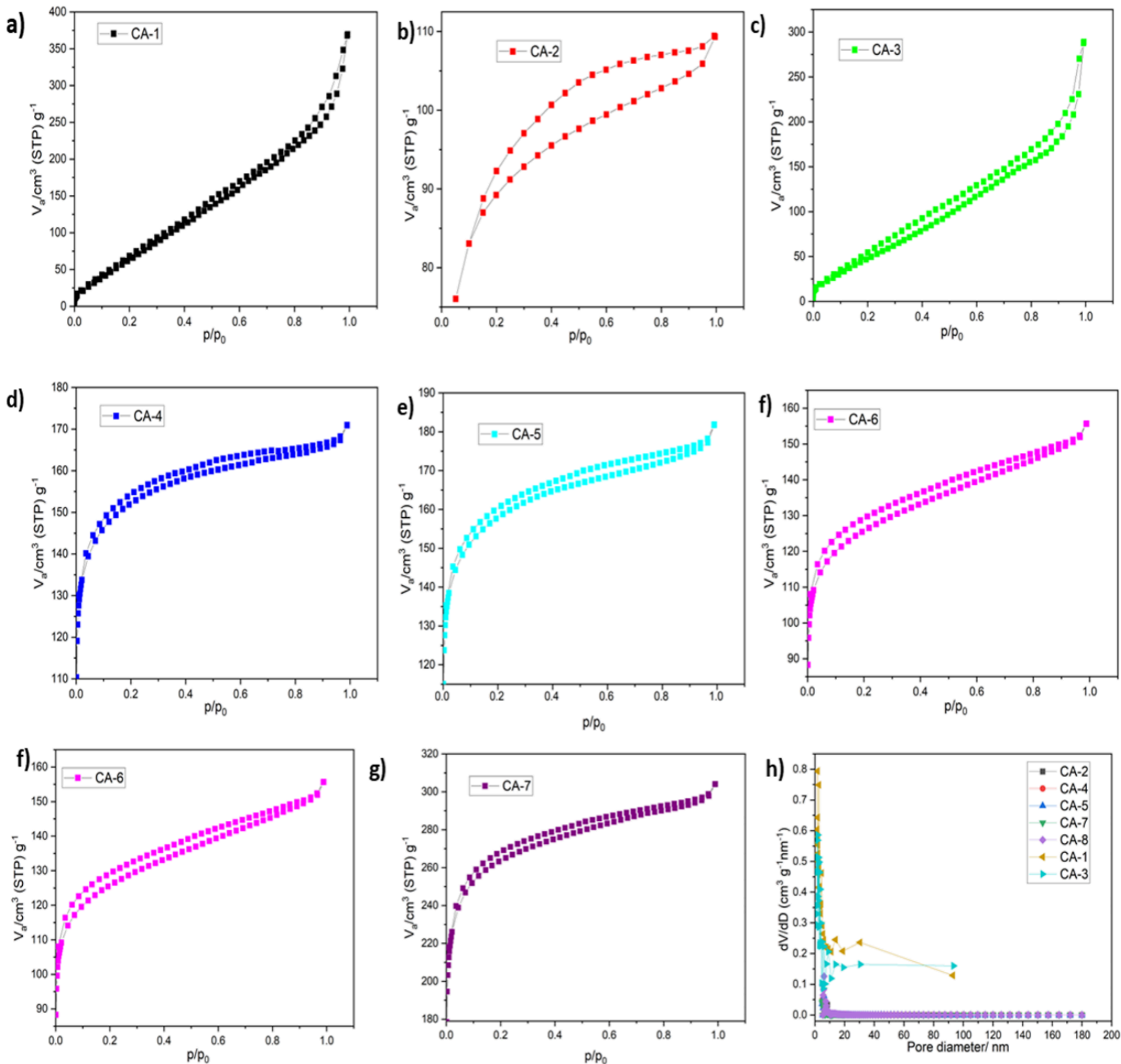


Figure 4

(a-g) N_2 adsorption/desorption isotherms and (h) pore size distribution of activated carbon samples (CA-2 to CA-7) with raw biomass CA-1

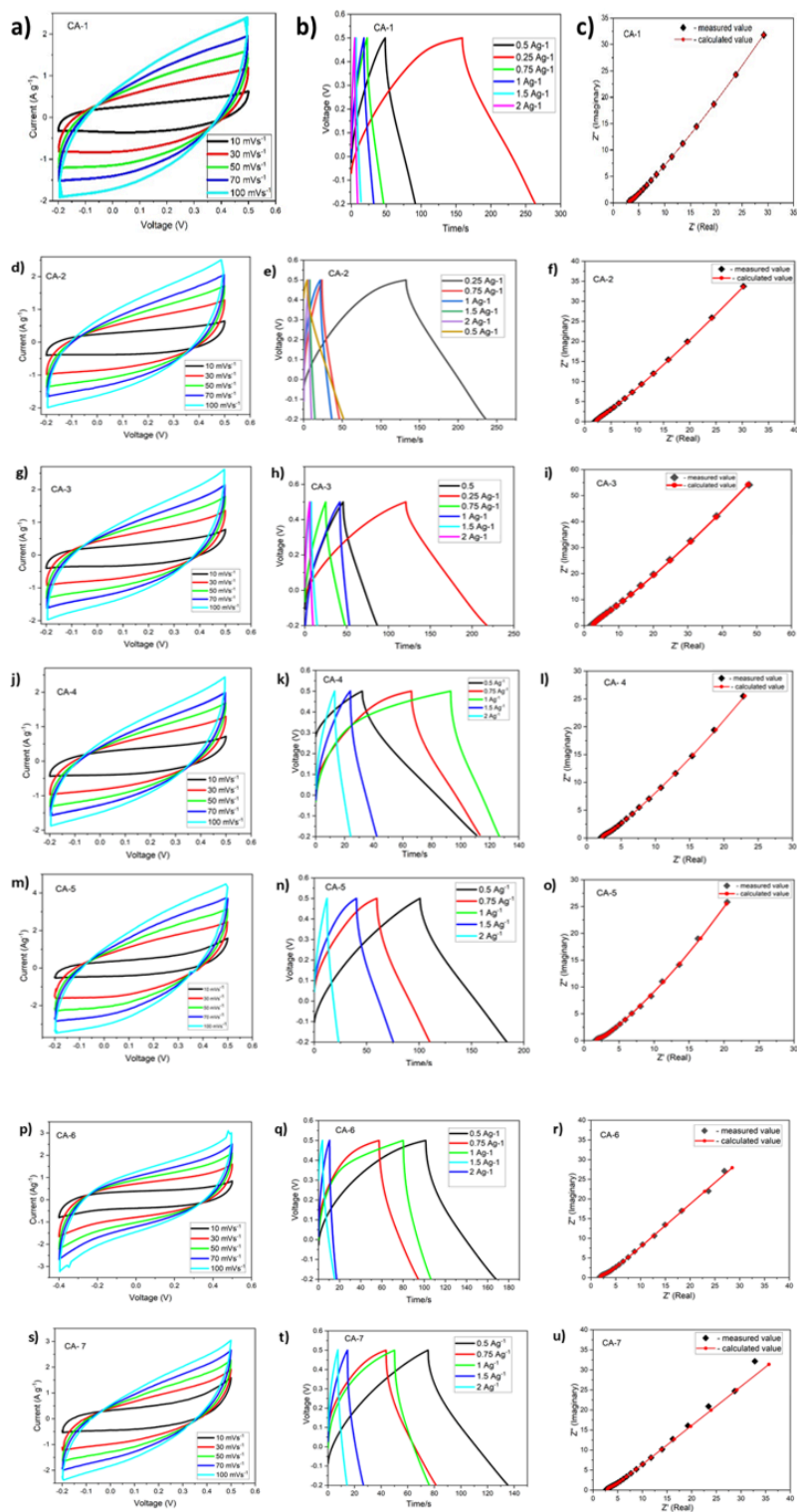


Figure 5

Electrochemical performance of the prepared carbon electrodes: cyclic voltammetry (CV), galvanostatic charge–discharge (GCD), and electrochemical impedance spectroscopy (EIS) analyses of CA-1 (BDC) ((a)–(c)), CA-2 ((d)–(f)), CA-3 ((g)–(i)), CA-4 ((j)–(l)), CA-5 ((m)–(o)), CA-6 ((p)–(r)), and CA-7 ((s)–(u))

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