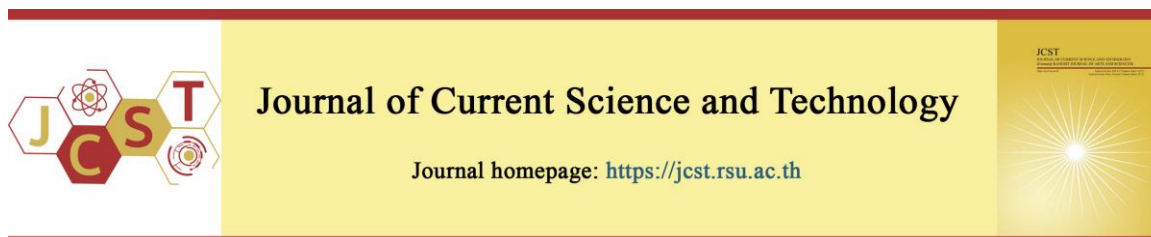


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Carbon-Based Electrodes from Agricultural Waste: Comparison of Textural and Electrical Properties

Naphatsorn Udompala
Songwuit Chanthee
Malee Santikunaporn*, 

Department of Chemical Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University,
Pathum Thani 12120, Thailand

*Corresponding author; E-mail: smalee@engr.tu.ac.th

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Abstract

Activated carbon-based electrodes were successfully derived from agri-food residues, namely palmyra palm fibers and apricot stone shells, via activation with potassium hydroxide at 750°C. Palmyra palm fiber activated carbon (PPA) and apricot stone shell activated carbon (ASA) were prepared, while commercial activated carbon (CAC) was used as received. All samples were characterized and electrically evaluated in a comparative study. Characterization results confirmed that ASA and PPA were successfully converted into carbonaceous materials. Scanning electron microscopy revealed a sponge-like porous structure in the PPA sample, whereas one-dimensional channel-like pores were observed in the ASA, and a smooth surface with randomly distributed cracks was observed in the CAC sample. Interestingly, the surface area of the activated carbon electrodes alone did not determine the specific capacitance. Although ASA possessed the highest surface area (1372.9 m² g⁻¹), it exhibited the lowest specific capacitance of 30.5 F g⁻¹ at 0.5 A g⁻¹. In contrast, PPA demonstrated the lowest surface area (502.5 m² g⁻¹) but delivered the highest specific capacitance of 47.6 F g⁻¹ at the same current density. Textural-electrical performance correlation analysis revealed that mesopore content (2–50 nm) has a greater impact on electrical capacitance than the overall specific surface area. Moreover, all carbon electrodes displayed quasi-rectangular cyclic voltammograms, consistent with the characteristic behavior of EDLCs. The PPA-based electrode exhibited excellent rate capability, retaining approximately 88% of its initial capacitance as the current density increased from 0.5 to 5.0 A g⁻¹, indicating its strong potential for practical EDLC applications.

Keywords: *activated carbon, apricot stone, electric double-layer capacitor, electrical properties, electrodes, palmyra palm, textural properties*

1. Introduction

Activated carbon materials have been extensively investigated in terms of their physical and chemical structures to enhance porous networks, surface area, and surface functionality. Owing to their high porosity, activated carbon materials have been widely utilized in various applications, including adsorption, catalysis, batteries, water treatment, and supercapacitors (Das & Sarma, 2025). In particular, for electrical energy

storage devices, porous activated carbon materials are employed as carbon-based electrodes because of their high thermal and chemical stability and tunable pore size, which contribute to maximizing electrical storage capacity (Yang et al., 2024). Activated carbon-based electrodes have attracted significant attention in electric double-layer capacitors (EDLCs), as the surface area and porosity of activated carbon materials strongly influence specific capacitance, cyclic voltammetry

behavior, and charge-discharge characteristics (Song et al., 2025). However, improving electrical capacitance is a complex process, as several factors affect capacitance, including electrolyte type, binder selection, electrolyte concentration, and the textural structure of the electrode (Verma et al., 2022; Zhu et al., 2016). Among these factors, the textural structure of the carbon electrode is one of the most critical parameters, as it directly influences ion transport and charge storage, thereby enhancing the overall electrical performance of EDLCs.

In EDLC systems, electrochemical performance is governed not only by the magnitude of the specific surface area but, more importantly, by the accessibility of electrolyte ions to the electrode interface (Liang et al., 2023; Shiraishi et al., 2024). While a high surface area provides abundant potential charge-storage sites, the effective utilization of these sites strongly depends on the pore size distribution and ion transport pathways within the carbon texture (Gong et al., 2025). Numerous studies have demonstrated that electrochemical capacitance and rate performance are influenced not only by surface area but also by pore size and pore architecture. Zhao et al. (2023) prepared hierarchical porous carbon from coconut shell biomass via one-step KOH activation, achieving a high specific surface area of $2143.6 \text{ m}^2 \text{ g}^{-1}$ with abundant micropores and mesopores centered at approximately 4 and 14 nm. In a three-electrode configuration, the optimized sample delivered a high specific capacitance of 317 F g^{-1} at 0.5 A g^{-1} and retained 216 F g^{-1} at 20.0 A g^{-1} , demonstrating excellent charge-storage capability and rate performance enabled by its hierarchical pore structure.

Similarly, Yang and coworkers (Yang et al., 2024) investigated activated carbons derived from camellia seed shells and found that the CSSC-KOH-1:3 sample, with a moderate specific surface area of $1219 \text{ m}^2 \text{ g}^{-1}$ and a well-balanced micro-mesoporous structure distributed in the 0.7–4.0 nm range, exhibited the highest specific capacitance of 305 F g^{-1} at 0.5 A g^{-1} . In contrast, the CSSC-KOH-1:5 sample, despite possessing a much higher surface area of $1981 \text{ m}^2 \text{ g}^{-1}$, delivered a lower capacitance of 193 F g^{-1} . These results clearly demonstrate that an optimized pore size distribution combining micropores for charge storage and mesopores for efficient ion transport is more critical for high-performance charge storage in EDLC systems than surface area alone. Furthermore, Fasakin et al. (2024) reported that activated carbon derived from cocoa pod husks with interconnected microporous and mesoporous textures achieved a maximum energy

density of 19 Wh kg^{-1} at 0.5 A g^{-1} in a symmetric device, further highlighting the importance of pore accessibility and ion transport pathways in enhancing EDLC performance.

The influence of pore size distribution on the behavior of EDLCs has been increasingly recognized. Micropores provide the primary sites for electric double-layer formation, whereas mesopores play a crucial role in facilitating electrolyte penetration and ion transport by acting as ion-buffering reservoirs and diffusion channels (Chitpreecha et al., 2026; Zhao et al., 2023). In contrast, excessive microporosity, particularly within the ultramicropore range, can restrict ion mobility and limit effective surface utilization under high-rate charge and discharge conditions. Consequently, achieving an appropriate balance between micropores for charge storage and mesopores for ion transport is essential for obtaining high capacitance together with good rate capability. Several studies have demonstrated that electrochemical capacitance correlates more strongly with mesopore contribution than with total surface area. Gamby et al. (2001) reported that carbon electrodes with increased mesoporous content exhibited higher capacitance without a corresponding increase in specific surface area, highlighting the limited impact of microporosity-dominated structures on practical charge storage. Similarly, Márquez-Montesino et al. (2023) showed that activated carbons with interconnected micro-mesoporous networks delivered superior capacitance and rate performance despite having comparable or even lower surface area. While Phan et al. (2019) reported that mesopores facilitate the migration of the electrolyte through ordered mesoporous carbons, Yang et al. (2016) concluded that larger pores of carbon aerogels facilitate the transport of electrolyte ions. Although research focuses on the effects of pore size distribution and micropore-mesopore ratios on the capacitance properties of carbon-based electrodes, only a limited number of publications have systematically investigated combined N_2/CO_2 textural analysis in relation to EDLC performance.

Biomass-derived activated carbons, such as betel palm shells (Torrarrit et al., 2025), rice husks (He et al., 2013), macadamia nut shell (Chaiammart et al., 2026), banana fibers (Fasakin et al., 2018), and apricot kernels (Onyilmaz et al., 2025), have emerged as promising candidates to address this challenge, as their intrinsic structural diversity enables porosity to be tailored through appropriate activation strategies (Dan & Le Luu, 2026). Among the available activation techniques, chemical activation using potassium hydroxide (KOH) has been

widely demonstrated to effectively generate hierarchical porosity and enhance electrolyte accessibility, thereby improving the electrochemical performance of EDLC electrodes. In the case of KOH activation, previous studies have investigated activated carbon derived from apricot stones, which provide attractive biomass precursors for producing hierarchically porous carbon materials (Echaroj et al., 2025). The pore size architecture of apricot-stone-derived activated carbons can be effectively tuned by varying the KOH-to-carbon ratio. Similarly, palmyra palm fibers have been explored as a carbon precursor capable of developing diverse porous structures when activated with different amounts of KOH (Sumangala Devi & Vivekanandhan, 2024). In addition, to develop hierarchical porosity, Onyilmaz et al. (2025) utilized defatted apricot kernels as a precursor for activated carbon through KOH/CO₂ activation. Although the porous structures of these biomass-derived activated carbons have been examined for EDLC electrode applications, systematic studies on their electrochemical performance, particularly in EDLC systems, remain limited. Moreover, the influences of pore size distribution, pore volume, and overall textural structure on electrochemically active interfaces are currently receiving increasing attention as key factors for enhancing EDLC performance (Zhang & Xie, 2025). Therefore, this work highlights the distinct carbon textural structures that govern electrochemical properties and their relevance to EDLC applications.

Palmyra palm fibers and apricot stone shells are abundant agricultural wastes in Thailand with significant potential as precursors for activated carbon production. Activated carbons derived from palmyra palm fibers and apricot stone shells, which have different shapes, pore structures, and surface areas, have been insufficiently investigated with respect to their electrochemical properties. Moreover, these agricultural carbon sources may deliver various textural structures that affect the electrical performance of supercapacitor electrodes. Therefore, the activated carbons derived from palmyra palm fibers and apricot stone shells were prepared via KOH chemical activation for systematic comparative study as carbon-based EDLC electrodes. The electrodes were evaluated in terms of pore size distribution through N₂ and CO₂ desorption, specific surface area, and structural and electrochemical properties. The differences in pore size distribution, surface area, and EDLC performance revealed in this study provide a basis for the rational design of biomass-derived activated carbon electrodes to improve supercapacitor performance.

2. Objectives

This study presents a comparative analysis of biomass-derived and commercial activated carbons, focusing on their textural characteristics and electrochemical performance in supercapacitor applications. The relationship between pore structure and EDLC behavior is systematically examined, with particular emphasis on mesoporosity.

3. Materials and Methods

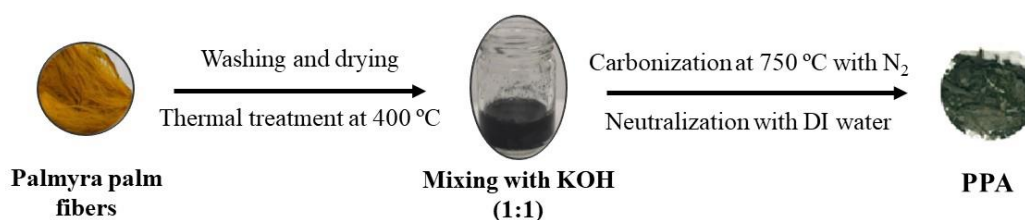
3.1 Materials

Waste apricot stone shells were obtained from Doi Kham Food Products Co., Ltd. (Thailand), while palmyra palm fibers were collected as waste from the local Thai dessert industry and used as the primary carbon precursors. For comparison, a commercial granular activated carbon (extra pure) was purchased from Loba Chemie Pvt. Ltd. (India). Potassium hydroxide (KOH), used as an electrolyte, and N-methyl-2-pyrrolidone (NMP, 99.5%), used as a solvent, were supplied by QReC (New Zealand). Polyvinylidene fluoride (PVDF, Mw $\approx$ 534,000), purchased from Sigma-Aldrich (Germany), was used as a binder. A conductive carbon black (Super P, $\geq$ 99%) was obtained from Thermo Scientific™ (Belgium). High-purity nitrogen and carbon dioxide gases (99.999%, UHP) were supplied by S.I. Technology Co., Ltd. (Thailand). All chemicals and reagents were used as received without further purification.

3.2 Preparation of Activated Carbons from Apricot Stone Shells and Palmyra Palm Fibers

As illustrated in Figure 1, palmyra palm fibers and apricot stone shells were first thoroughly washed with deionized water to remove surface impurities. The raw materials were then dried in an oven at 80°C for 12 h to eliminate residual moisture. Subsequently, the dried precursors were thermally treated at 400°C for 1 h to produce biochar. The resulting biochar from each material was mixed with KOH solution at a weight ratio of 1:1 and stirred at 80°C for 2 h, followed by drying at 100°C overnight. The dried mixtures were then calcined at 750°C for 1 h under a nitrogen atmosphere, using a controlled heating rate of 5°C min⁻¹. The obtained activated carbons were denoted as apricot stone shell activated carbon (ASA) and palmyra palm fiber activated carbon (PPA). The ASA and PPA samples were repeatedly washed with deionized water until neutral pH was achieved and then dried and stored in a desiccator for further use.

Preparation of activated carbon from palmyra palm fibers (PPA)



Preparation of activated carbon from apricot stone shells (ASA)

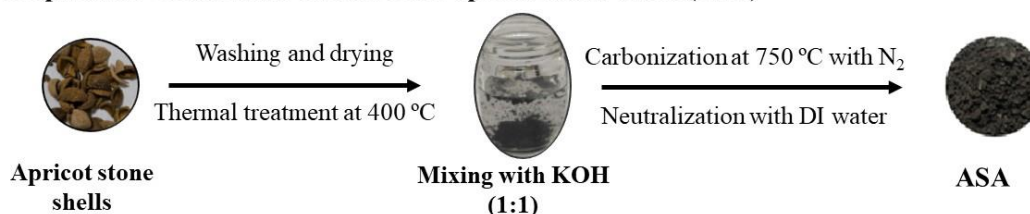


Figure 1 Schematic illustration of the preparation of activated carbons from palmyra palm fibers and apricot stone shells

For comparative studies, commercial granular activated carbon (CAC) was used without further purification.

3.3 Characterization Techniques

The surface morphologies of the activated carbon samples were examined using scanning electron microscopy (SEM, JEOL JSM-7800F). Powder X-ray diffraction (XRD) patterns were recorded on a Shimadzu XRD-6000 diffractometer with Cu K α radiation ($\lambda = 0.154$ nm), with data collected over a 2θ range of $10 - 60^\circ$ at a scan rate of 2° min^{-1} . The elemental composition of the samples was examined using an EDX-LE X-ray fluorescence (XRF) spectrometer (Shimadzu, Japan). Textural properties were analyzed by gas adsorption-desorption isotherms using an Autosorb iQ-MP/XR adsorption analyzer (Quantachrome Instruments, USA). Nitrogen (N₂) adsorption measurements were conducted at -196°C , while carbon dioxide (CO₂) adsorption measurements were performed at 0°C . Prior to analysis, all samples were degassed under vacuum at 280°C for 18 h to remove adsorbed gases and moisture. The specific surface area (SSA) was calculated using the Brunauer–Emmett–Teller (BET) method, and the total pore volume was estimated from the N₂ adsorption isotherms at a relative pressure close to unity ($P/P_0 \approx 0.99$). Pore size distributions were determined using density functional theory (DFT) models. For N₂ adsorption data, the quenched

solid density functional theory (QSDFT) model assuming slit-shaped pores were applied, whereas the non-local density functional theory (NLDF) model with the same pore geometry was employed for CO₂ adsorption to evaluate ultramicropores smaller than 0.8 nm. Different DFT models were used for N₂ and CO₂ analyses due to the limitations of the AsiQwin software (version 5.21), which supports only a single DFT model for CO₂ adsorption. Although this approach may introduce minor quantitative differences near the ultramicropore region (~ 1 nm), the comparative interpretation of pore structure among the samples remains reliable (Brodawka et al., 2022).

3.4 Electrode Preparation and Electrochemical Measurement

Working electrodes were prepared by casting a slurry containing activated carbon (AC) (80 wt%), PVDF (10 wt%) and carbon black (10 wt%) dispersed in NMP. The slurry was stirred for 12 h, coated onto stainless steel foil using a doctor blade, and subsequently dried at 120°C under vacuum for 12 h. Carbon black is used in the carbon-based electrodes of supercapacitors primarily to improve electrical conductivity and reduce internal resistance. The electrical conductivity in carbon-based supercapacitor electrodes is crucial for reducing internal resistance, enhancing power density, and improving the charge/discharge rate. High conductivity improves the

speed of charge transfer and electron transport within the electrode materials (Liu et al., 2025). PVDF is commonly used because of its exceptional chemical and thermal stability and strong adhesive properties. It acts as a robust binder in strong acid or base electrolytes for carbon electrode materials in supercapacitors (Yang et al., 2024). Symmetric two-electrode cells were assembled using identical electrodes with filter paper as the separator. Electrochemical measurements were performed at room temperature using an Autolab PGSTAT204 potentiostat (Metrohm Autolab, Netherlands) in 3 M KOH aqueous electrolyte. Cyclic voltammetry (CV) was conducted over a voltage window of 0 – 1 V at scan rates from 0.005 to 0.2 V s⁻¹. Galvanostatic charge-discharge (GCD) measurements were carried out within the same voltage range at current densities of 0.2 – 5 A g⁻¹. The specific capacitance (C_{sc} , F g⁻¹) was calculated from the GCD profiles using Equation (1):

$$C_{sc} \text{ (F g}^{-1}\text{)} = I \times t_d / (\Delta V \times m) \quad (1)$$

where I represents the discharge current (A), t_d denotes the discharge time (s), ΔV signifies the potential window (V), and m corresponds to the active carbon mass of the electrode (g).

The mass loadings of active materials were approximately 8.8, 4.8, and 1.8 mg cm⁻² for ASA, PPA, and CAC electrodes, respectively. The specific capacitance values were calculated based on the active mass of each electrode to ensure reliable comparison among samples with different mass loadings.

4. Results and Discussion

4.1 Material Characterization

Activated carbons derived from ASA and PPA were synthesized via a two-step process consisting of carbonization followed by KOH activation. The resulting materials were neutralized and oven-dried at 100°C to remove residual KOH, impurities, and moisture. Comprehensive characterization was performed to evaluate their physicochemical and structural properties. Surface morphology and pore structure were examined using SEM, while XRD was employed to assess the crystallinity and structural characteristics of the carbon matrix.

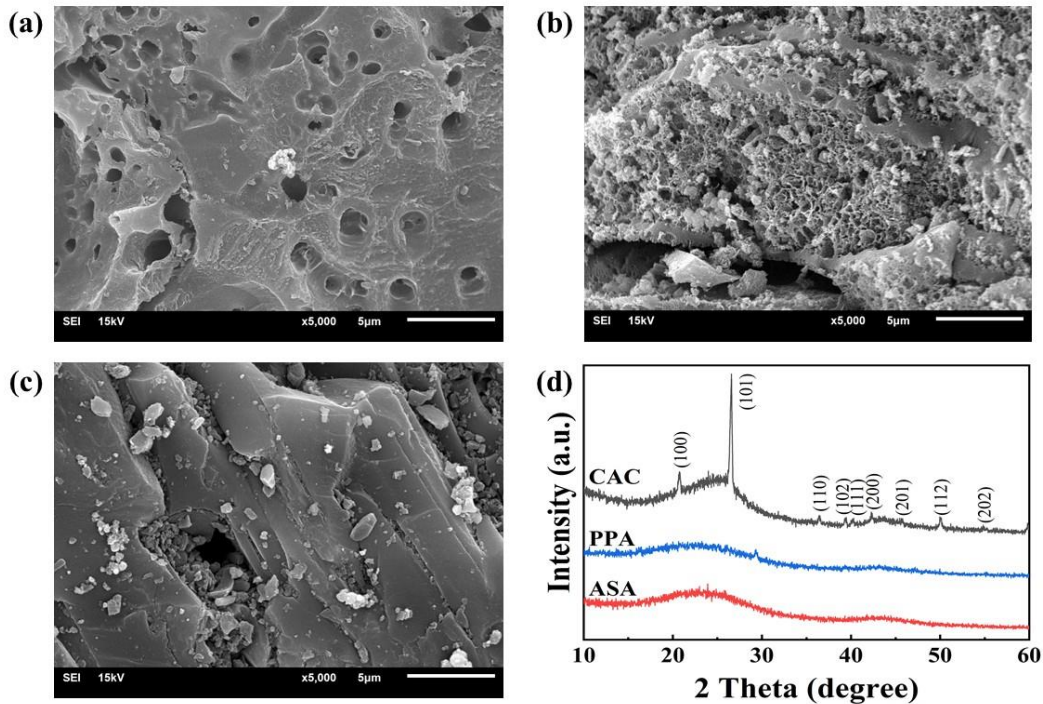


Figure 2 SEM images of (a) ASA, (b) PPA, (c) CAC and (d) XRD patterns of ASA, PPA, and CAC

Figures 2(a) – 2(c) show the surface morphologies of ASA, PPA, and CAC, respectively. The ASA sample (Figure 2(a)) exhibited a relatively smooth surface with a one-dimensional, channel-like pore structure with an average diameter of approximately 9 μm . The PPA sample (Figure 2(b)) showed a sponge-like morphology with irregularly distributed pores across the surface. The pore structure appeared highly interconnected, forming a three-dimensional porous network. In contrast, the CAC sample (Figure 2(c)) presented a relatively smooth and uniform surface. Small cracks were observed to be randomly distributed over the surface. In addition, several particulate features were detected on the CAC surface. At the magnification used, no well-defined pores were clearly visible in the CAC sample.

The XRD patterns of the activated carbon samples are shown in Figure 2(d). All samples exhibit two broad diffraction peaks centered at approximately $2\theta \approx 25^\circ$ and 44° , which can be indexed to the (002) and (100) planes of hexagonal graphite, respectively. The broad and low-intensity nature of these peaks confirms the predominantly amorphous and disordered nature of the prepared activated carbons, consistent with the disordered morphologies observed in the SEM images. Among the samples, CAC exhibits slightly sharper diffraction peaks, suggesting a higher degree of structural ordering compared with ASA and PPA. In contrast, the broader peaks observed for ASA and PPA reflect smaller graphitic domains and a higher degree of structural disorder, which are typical characteristics of biomass-derived activated carbons. Although Raman spectroscopy is frequently employed to quantify defect density (I_D/I_G ratio), the XRD results in this study provide clear evidence of structural disorder. Additionally, the strong diffraction peaks appearing in the CAC sample were assigned to the SiO_2 phase, indicating the presence of inorganic impurities in the CAC sample, in agreement with the XRF results presented in Table 1.

Table 1 Inorganic impurities of all activated carbon samples

Impurities	PPA	ASA	CAC
Si, %	-	-	30.43
Ca, %	67.19	46.73	26.36
K, %	25.19	48.29	4.90
Fe, %	2.20	3.60	13.35
Others, %	5.42	1.38	24.96

4.2 N_2 and CO_2 Adsorption-Desorption Isotherms

Nitrogen and carbon dioxide adsorption-desorption measurements were conducted to determine the specific surface areas and pore size distributions of the ASA, PPA, and CAC samples. The N_2 adsorption-desorption isotherms of ASA, PPA, and CAC are shown in Figures 3(a), 3(d), and 3(g), respectively. As shown in Figures 3(a) and 3(g), the ASA and CAC samples exhibit Type I isotherms according to the IUPAC classification, indicating predominantly microporous structures. As summarized in Table 2, ASA displays the highest specific surface area of $1372.9 \text{ m}^2 \text{ g}^{-1}$, with a total pore volume of $0.89 \text{ cm}^3 \text{ g}^{-1}$ and an average pore size of 2.59 nm. In comparison, CAC shows a moderate surface area of $726.0 \text{ m}^2 \text{ g}^{-1}$, a pore volume of $0.41 \text{ cm}^3 \text{ g}^{-1}$, and an average pore size of 2.28 nm. The superior surface area of ASA can be attributed to its highly developed one-dimensional pore channels extending throughout the carbon matrix. In contrast, the PPA sample (Figure 3(d)) exhibits a Type II isotherm with an H4 hysteresis loop in the relative pressure (P/P_0) range of 0.4 – 0.9, indicating the coexistence of microporous and mesoporous structures (Thommes et al., 2015). The PPA sample shows a specific surface area of $502.5 \text{ m}^2 \text{ g}^{-1}$ and a pore volume of $0.49 \text{ cm}^3 \text{ g}^{-1}$, with an average pore size of 3.91 nm. The contributions of micropores to the total surface area were estimated to be 84%, 86%, and 95% for ASA, PPA, and CAC, respectively, indicating that microporosity is dominant in all samples. Differences in mesopore content among the samples were observed.

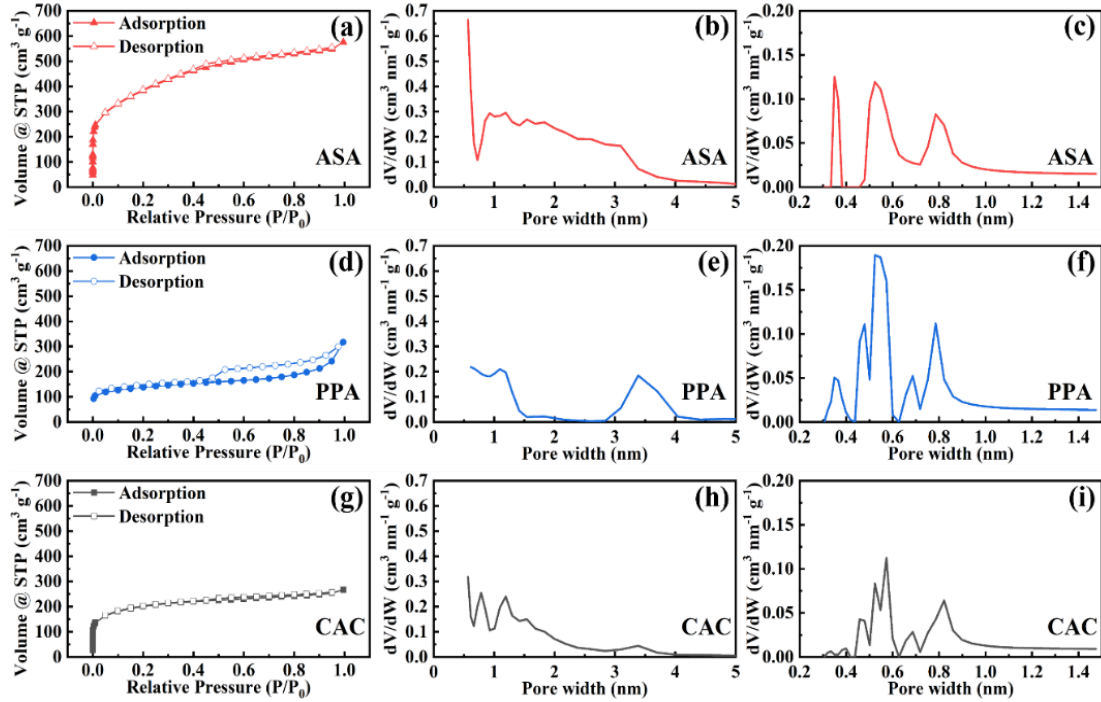


Figure 3 (a, d, g) N₂ adsorption-desorption isotherms, (b, e, h) pore size distributions obtained from the N₂ desorption technique, and (c, f, i) pore size distributions obtained from the CO₂ desorption technique of ASA, PPA, and CAC samples

Table 2 Summary of structural parameters for all activated carbon samples

Sample	SSA _{BET}	SSA _{micro,DFT}	SSA _{micro,DFT} contribution	V _{total}	Average pore size	Specific capacitance	
	[m ² g ⁻¹]	[m ² g ⁻¹]	[%]			At 0.5 A g ⁻¹	At 5 A g ⁻¹
ASA	1372.9	1160.0	84	0.89	2.59	30.5	20.4
PPA	502.5	433.6	86	0.49	3.91	47.6	41.8
CAC	726.0	689.7	95	0.41	2.28	31.5	24.4

The pore size distributions derived from N₂ desorption (Figures 3(b), 3(e), and 3(h)) reveal distinct pore characteristics. ASA (Figure 3(b)) exhibits a broad pore size distribution ranging from 1.0 to 3.5 nm with the highest cumulative pore volume. PPA (Figure 3(e)) shows two broad peaks centered at approximately 1.0 – 1.5 nm and 3.0 – 4.0 nm, consistent with its H4 hysteresis loop and indicative of a hierarchical pore structure (Thommes et al., 2015). The CAC sample (Figure 3(h)) displays multiple narrow peaks at approximately 0.8, 1.2, and 1.5 nm, along with a broader distribution between 3.0 and 4.0 nm, suggesting a pore system dominated by ultra-micropores and micropores with limited mesoporosity.

Since N₂ gas has limited ability to accurately probe pores smaller than approximately 0.8 nm, CO₂ gas measurements at 0°C were employed to characterize the ultramicropore region using the NLDFT slit-pore

model. The CO₂-derived pore size distributions (Figures 3(c), 3(f), and 3(i)) indicate that ASA contains three dominant ultramicropore peaks at approximately 0.35, 0.52, and 0.78 nm. PPA exhibits four peaks at 0.35, 0.52, 0.69, and 0.79 nm, while CAC shows ultramicropore peaks centered at 0.46, 0.57, 0.69, and 0.82 nm. By combining the pore size distributions obtained from N₂ and CO₂ measurements, the overall pore structure composition was quantified. ASA consists of approximately 22% ultramicropores (< 0.8 nm), 39% micropores (0.8 – 2.0 nm), and 39% mesopores (> 2 nm). PPA contains 17% ultramicropores, 26% micropores, and 57% mesopores, whereas CAC exhibits 32% ultramicropores, 44% micropores, and only 24% mesopores. These results confirm that PPA possesses the highest mesopore fraction despite its lower total surface area, while CAC exhibits the most restrictive pore architecture, characterized by a high ultramicropore content and limited mesoporosity.

4.3 Electrochemical Properties

The electrochemical performance of the samples was evaluated using cyclic voltammetry and galvanostatic charge-discharge measurements in symmetric two-electrode cells with a 3 M KOH electrolyte. Figures 4(a) – 4(c) present the CV curves recorded at scan rates ranging from 0.005 to 0.200 V s⁻¹, while the corresponding GCD profiles at current densities of 0.2 – 5.0 A g⁻¹ are shown in Figures 4(d) – 4(h).

4.3.1 Cyclic Voltammetry Analysis

Figures 4(a) – 4(c) present the cyclic voltammetry (CV) profiles of the ASA, PPA, and CAC electrodes, respectively, recorded at scan rates ranging from 0.005 to 0.200 V s⁻¹. All electrodes exhibit quasi-rectangular CV profiles over the investigated scan rate range, which is characteristic of electric double-layer capacitor behavior (Zhao et al., 2023). At low scan rates (< 0.020 V s⁻¹), the CV

curves maintain well-defined rectangular shapes with nearly symmetric current responses during the forward and reverse scans, indicating efficient ion diffusion into the accessible pore networks and effective utilization of the electrochemically active surface area (Onyilmaz et al., 2025). With increasing scan rates from 0.020 to 0.200 V s⁻¹, slight deviations from ideal rectangularity are observed for all electrodes. This behavior is commonly attributed to increased ion transport resistance and limited electrolyte penetration into smaller pores at higher scan rates, rather than a change in the charge-storage mechanism (Onyilmaz et al., 2025; Wang et al., 2021). Despite differences in textural properties and surface areas, ASA, PPA, and CAC exhibit comparable CV shapes, suggesting similar and stable capacitive behavior. However, despite the SiO₂ detected in the XRD pattern of CAC, no oxidation or reduction peak was observed in the CV curve, resulting in a quasi-rectangular shape.

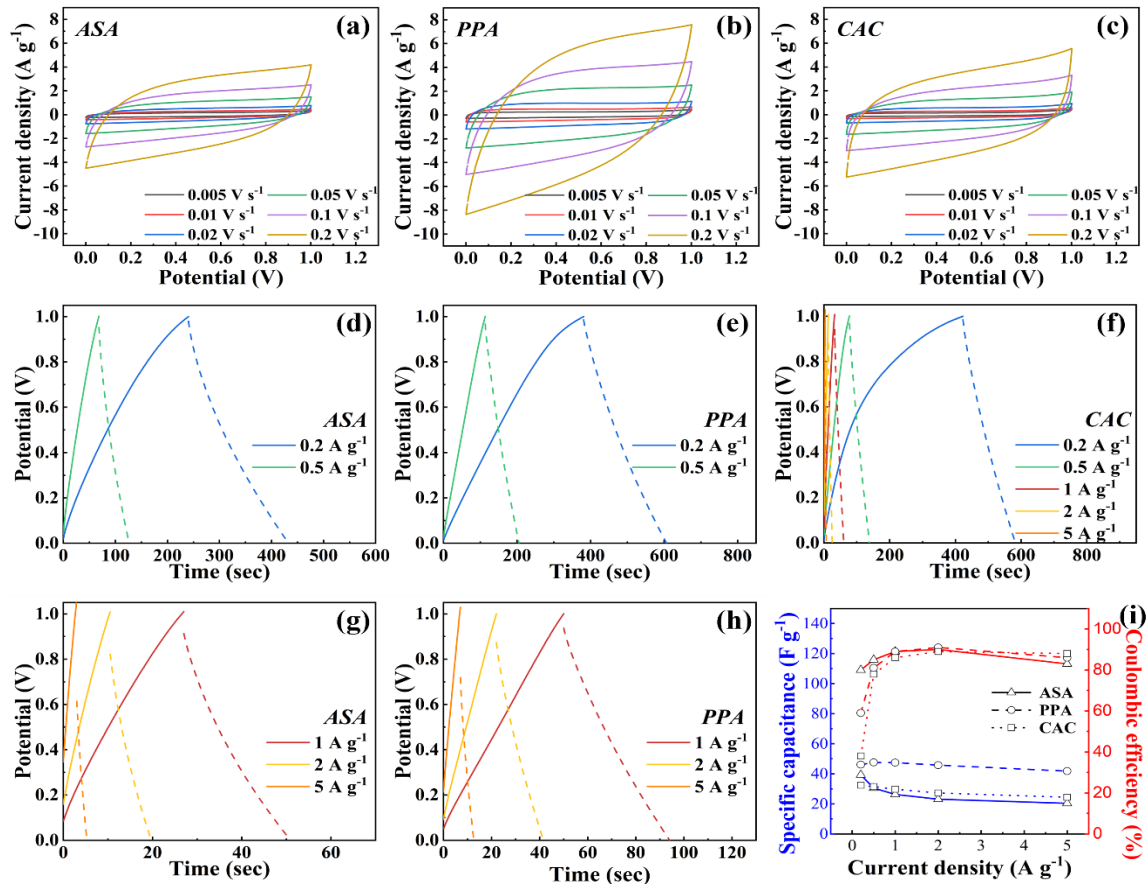


Figure 4 Electrochemical characterization of ASA, PPA, and CAC: CV curves at various scan rates (0.005 – 0.200 V s⁻¹) for (a) ASA, (b) PPA, and (c) CAC; GCD profiles at current densities of 0.2 – 5.0 A g⁻¹ for (d, g) ASA, (e, h) PPA, and (f) CAC; (i) specific capacitance and coulombic efficiency as functions of current density for all samples; ASA (Δ), PPA (○) and CAC (□)

4.3.2 Galvanostatic Charge-Discharge Analysis

Figures 4(d) – 4(h) show the galvanostatic charge-discharge (GCD) curves of the ASA, PPA, and CAC electrodes measured at various current densities. All electrode samples exhibit nearly linear and symmetric charge-discharge profiles, which are characteristic of EDLC behavior. The close symmetry between the charge and discharge branches indicates good electrochemical reversibility for all electrodes. At a current density of 0.5 A g^{-1} , the specific capacitances of ASA, PPA, and CAC are calculated to be 30.5, 47.6, and 31.5 F g^{-1} , respectively. Notably, the PPA electrode delivers the highest specific capacitance despite having the lowest BET surface area. The observation suggests that capacitance is governed not only by the surface area of the carbon electrode but also by the micropore and mesopore contents. As mentioned in the report, microporosity enhances electrostatic charge accumulation, whereas mesoporosity improves ion transport pathways. (Sun et al., 2022) In particular, the larger mesopore fraction and wider average pore size of PPA facilitate more effective ion transport, in agreement with previously reported studies (Wang et al., 2021; Yu et al., 2018). The ASA and CAC electrodes exhibit similar capacity, although ASA has a higher specific surface area than CAC because ASA has a lower micropore volume ($0.32 \text{ cm}^3 \text{ g}^{-1}$).

At the lowest current density (0.2 A g^{-1}), the GCD profiles of PPA and CAC exhibit slight distortion from ideal triangularity as a result of reduced coulombic efficiency, as shown in Figure 4(i). The ASA electrode shows the highest coulombic efficiency due to its highly symmetrical triangular charge-discharge curve. This behavior may be attributed to electrolyte ion diffusion and partial irreversible ion adsorption at low current density, which has been reported for highly microporous activated carbon electrodes. (Gandla et al., 2021; Pandolfo & Hollenkamp, 2006; Zhang & Zhao, 2009). The electrochemical performance at different current densities is presented in Table 3. At the current densities above 0.2 A g^{-1} , PPA demonstrates superior rate capability and retains approximately 88% of its initial capacitance, whereas ASA and CAC retain about 67% and 77% of their initial capacitance, respectively. The higher electrochemical performance of PPA indicates more efficient ion transport within the porous network during the rapid charge-discharge process. The cycling stability of the PPA electrode was further evaluated over 5000 charge-discharge cycles at 1 A g^{-1} , as illustrated in Figure 5. The electrode retained approximately 80% of its initial capacitance after 5000 cycles, while maintaining coulombic efficiency close to 100% throughout the cycling test.

Table 3 Electrochemical performance at different current densities.

Sample	Current density [A g^{-1}]	Specific capacitance [F g^{-1}]	Coulombic efficiency	Energy density [Wh kg^{-1}]	Power density [W kg^{-1}]
ASA	0.2	39.3	80%	5.2	97.9
	0.5	30.5	85%	3.8	237.9
	1.0	26.3	89%	3.0	456.5
	2.0	23.1	90%	2.2	822.1
	5.0	20.4	83%	1.1	1534
PPA	0.2	46.1	59%	6.2	98.0
	0.5	47.6	81%	6.2	241.8
	1.0	47.5	89%	5.8	468.6
	2.0	45.8	91%	4.9	873.1
	5.0	41.8	86%	3.0	1796.0
CAC	0.2	32.4	38%	4.4	98.4
	0.5	31.5	78%	4.1	241.9
	1.0	29.7	86%	3.7	470.9
	2.0	27.3	89%	2.9	880.1
	5.0	24.4	88%	1.7	1791.2

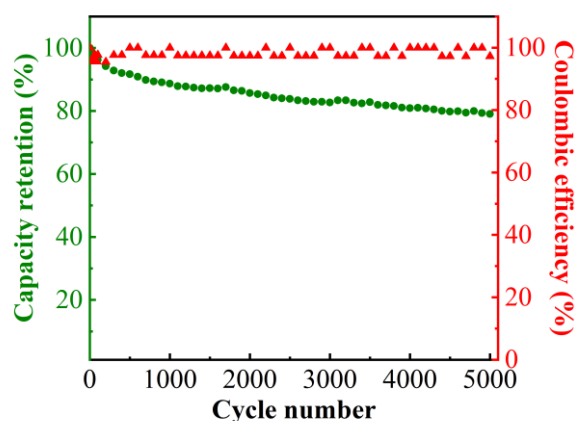


Figure 5 Cycling stability and coulombic efficiency of the PPA sample at 1 A g⁻¹ after 5000 cycles

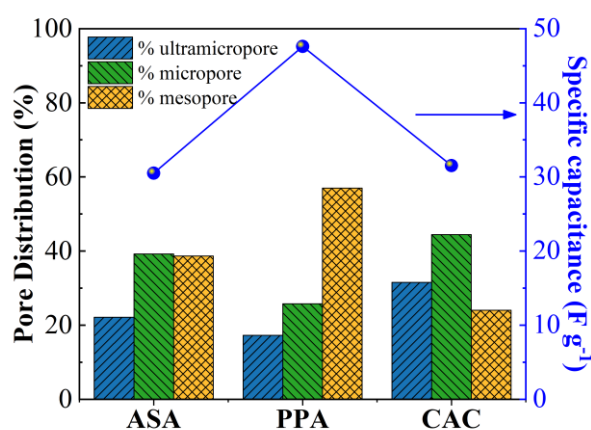


Figure 6 Structure-performance correlation between pore size distribution and specific capacitance for ASA, PPA, and CAC electrodes

Table 4 Comparison of electrochemical performance (at 0.5 A g⁻¹) of biomass-derived activated carbons for supercapacitor applications

Sample	KOH/biochar ratio	Carbonization (°C)	SSA _{BET} (m ² g ⁻¹)	Specific capacitance (F g ⁻¹)	KOH concentration (M)	Energy density (Wh kg ⁻¹)	Power density (W kg ⁻¹)	Reference
Camellia seed shells	3.0	800	1219	62.9	3	15.4	195.0	Yang et al., 2024
Coconut shell carbon	2.0	800	1299	97.8	6	13.5	250.0	Zhao et al., 2023
Sugarcane bagasse	3.0	750	3549	60.0	6	8.3	253.5	Kang et al., 2024
Shea butter shells	1.5	800	1234	91.6	6	12.7	375.1	Ampong et al., 2024
Macadamia nutshell waste	3.0	600	1362	36.3	6	5.4	2500.0	Chaiammart et al. 2026
Natural cattail fibers	1.0	800	841	32.0	3	3.6	1249.6	Wang et al., 2022
ASA	1.0	750	1373	30.5	3	3.8	237.9	This work
PPA	1.0	750	502	47.6	3	6.2	241.8	This work

Note: SSA_{BET} = Brunauer–Emmett–Teller specific surface area; “This work” indicates data obtained from the present study.

4.4 Structure-performance Relationships and Comparative Analysis

Figure 6 presents a comparative structure-performance analysis by correlating the pore size distribution with the specific capacitance of the ASA, PPA, and CAC electrodes. Although ASA exhibits the highest total surface area, its specific capacitance is lower than that of PPA, indicating that total surface area alone is not the key factor governing electrochemical performance. In contrast, PPA possesses the highest mesopore volume and delivers the highest specific capacitance, highlighting the importance of suitable pore accessibility and efficient ion transport. This correlation demonstrates that mesopores act as effective ion-buffering reservoirs and transport pathways, facilitating electrolyte penetration and reducing diffusion resistance during rapid charge-discharge processes (Zhao et al., 2023; Zhu et al., 2015). In contrast, ASA and CAC contain a higher proportion of micropores and ultramicropores, which, despite contributing to a large surface area, can restrict ion accessibility under dynamic operating conditions. The influence of pore architecture is further reflected in the internal resistance behavior discussed in the GCD analysis. PPA exhibits a smaller IR drop at elevated current densities, consistent with reduced resistive losses and faster ion migration. ASA shows a larger IR drop, while CAC displays intermediate behavior, further supporting the critical role of pore connectivity and accessibility in governing electrochemical kinetics (Byatarayappa et al., 2023). Overall, these results reinforce the conclusion that appropriate pore size distribution and connectivity are more critical than total surface area for maximizing EDLC performance.

Compared with other activated carbons reported in the literature (Table 4), carbon electrodes derived from other natural sources provide high power density. However, some carbon materials possessing high specific surface area exhibit moderate electrical capacitance (at a current density of 0.5 A g^{-1}). Although ASA and PPA show low electrical capacity, they provide acceptable power densities of 237.9 and 241.8 W kg^{-1} , respectively. The literature presents energy density in the range of $3.6 - 15.4 \text{ Wh kg}^{-1}$ due to the synergistic interaction among surface area, activating ratio, and structural nature. Nevertheless, improvement of electrical capacity using activated carbon derived from natural sources remains challenging due to its textural and porous structure in nature.

5. Conclusion

In this work, activated carbons derived from palmyra palm fiber and apricot stone shell wastes were successfully prepared via chemical activation using KOH and employed as symmetric carbon-based electrodes for supercapacitor applications. Despite its relatively low specific surface area, the PPA-derived carbon delivers a high specific capacitance of 47.6 F g^{-1} with 6.2 Wh kg^{-1} and excellent rate performance, highlighting the dominant role of mesopore volume rather than total surface area in governing electrochemical performance. The mesopore structure of the activated carbon electrodes significantly influences their charge-discharge behavior and ion transport characteristics. Moreover, both materials exhibit quasi-rectangular CV profiles, good electrochemical reversibility, and acceptable power and energy densities, demonstrating their suitability for practical supercapacitor applications. In addition, the PPA electrode demonstrated approximately 80% capacitance retention after 5000 charge-discharge cycles at 1.0 A g^{-1} , indicating stable electrochemical reversibility. However, further improvements in long-term cycling stability and conductivity optimization could enhance its performance for practical supercapacitor applications.

6. Abbreviations

Abbreviation	Full Term
ASA	Apricot stone shell activated carbon
BET	Brunauer-Emmett-Teller
CAC	Commercial activated carbon
CV	Cyclic voltammetry
DFT	Density functional theory
EDLC	Electric double-layer capacitors
GCD	Galvanostatic charge-discharge
NMP	N-methyl-2-pyrrolidone
PPA	Palmyra palm fiber activated carbon
PVDF	Polyvinylidene fluoride
SEM	Scanning electron microscopy
SSA	Specific surface area
XRD	Powder X-ray diffraction

7. CRediT Statement

Naphatsorn Udompala: Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization

Songwuit Chanthee: Conceptualization, Methodology, Validation, Writing – Review & Editing, Supervision

Malee Santikunaporn: Conceptualization, Methodology, Investigation, Resources, Writing – Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisition

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