

Banana peel-derived carbon for supercapacitor electrodes: Carbonization temperature-dependent structural and electrochemical properties

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Abstract

Banana peels (*Musa ABB*, Namwa cultivar) were utilized as sustainable precursors for the production of carbonaceous materials for supercapacitor electrodes. Carbonization was performed at temperatures ranging from 500 to 1000 °C. During carbonization, CO₂ and H₂O were released, promoting physical self-activation and pore development. X-ray diffraction confirmed the presence of KCl and K₂CO₃ phases, which were removed after washing with HCl and deionized water, leaving only amorphous carbon. Iodine adsorption analysis revealed that increasing carbonization temperature enhanced porosity, with iodine adsorption values of -10.42, 194.20, 150.04, 485.80, 471.44, and 325.09 mg·g⁻¹ at 500, 600, 700, 800, 900, and 1000 °C, respectively. This trend is in agreement with the change in surface area with carbonization temperature, which increased from 500 to 800 °C (382.403–800.846 m²·g⁻¹) and decreased at 900 and 1000 °C (684.595 and 156.881 m²·g⁻¹, respectively). The carbon obtained at 800 °C (CC800) delivered the highest specific capacitance, 169 F·g⁻¹ at 0.5 A·g⁻¹ in a 1 M H₂SO₄ electrolyte, owing to its highest specific surface area (800.846 m²·g⁻¹). Additionally, the redox peaks associated with surface functional groups formed during carbonization would further enhance the capacitance of all carbons. These results demonstrate that banana peel-derived carbon, synthesized via carbonization, exhibits a high surface area and excellent charge storage capability.

Keywords: Self-activation, Carbonization temperature, Biomass-derived carbon, Porous carbon, Supercapacitors

1. Introduction

Biomass materials derived from agriculture, forestry, animal waste, food residues, and other biodegradable municipal wastes are increasingly recognized as a global management challenge, as their improper disposal can negatively impact the environment. Among the strategies for valorizing biomass waste, the preparation of carbon materials as electrodes for electric double-layer capacitors (EDLCs) has been extensively studied due to their high electrical conductivity and porous structure [1, 2]. This approach not only contributes to effective biomass waste management but also provides a potential solution for energy storage challenges.

Carbon materials have been developed in various forms, including biochar and activated carbon (AC). Both are typically produced through pyrolysis; however, they differ in feedstock selection, pyrolysis conditions, and post-treatment, particularly the activation methods, which can be physical or chemical. Physical activation is relatively low-cost, relying on inexpensive activating agents such as steam, CO₂, or air [3]. In contrast, chemical activation involves acidic agents (e.g., phosphoric, nitric, sulfuric, and hydrochloric acids), neutral salts (e.g., K₂CO₃, ZnCl₂, and CaCl₂), or alkaline agents (e.g., NaOH and KOH). Although physical activation generally yields lower surface area, it is safer because it avoids residual chemicals [2, 4, 5]. Physical self-activation is a method in which pyrolysis gases released from biomass during carbonization act as activating agents, enabling the preparation of porous carbon with no chemical additives. Chemical self-activation follows the same mechanism as conventional chemical activation, which uses a chemical agent naturally impregnated in biowaste, such as CaCO₃ in oyster shells [6], hydroxyapatite (HA, Ca₅(PO₄)₃(OH)) in bone [7], and Ca and K ions in cabbage [2], among others. This environmentally friendly approach integrates carbonization and activation into a single step, simplifying the preparation process and enhancing activation efficiency [3, 8].

Thus, in this work, we investigated the use of banana peels (*Musa ABB*, Namwa cultivar) for carbon material preparation, an abundant biomass resource in Thailand that is rich in potassium (K) [9]. During pyrolysis, potassium can promote the formation of compounds such as KCl and K₂CO₃, which facilitate the development of a highly porous carbon structure [2, 8, 10, 11]. In this study, high-porosity carbon materials were synthesized from Namwa banana peels via a self-activation method for use as carbon electrodes in electric double-layer capacitor applications.

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2. Materials and methods

2.1 Materials

Namwa banana peels from Khon Kaen, Thailand, were used as a carbon source for electrode fabrication. Sulfuric acid (H_2SO_4 , 98%) was purchased from RCI Labscan. Sodium thiosulfate 5-hydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$, 99.5%) and iodine (I_2 , 99.8%) were obtained from KemAUS. N-methyl-2-pyrrolidone (NMP, $\text{C}_5\text{H}_9\text{NO}$, 99%), and polyvinylidene difluoride (PVDF, $(\text{CH}_2\text{CF}_2)_n$) were sourced from Sigma Aldrich. Carbon black (CB, 99%) was purchased from Alfa Aesar. All materials were of analytical reagent grade and used with no further purification.

2.2 Synthesis

Carbonized carbons (CCs) derived from Namwa banana peels were self-activated by carbonization at 500–1000 °C at a heating rate of $10\text{ }^\circ\text{C} \cdot \text{min}^{-1}$ for 2 h in a tubular furnace under an argon (Ar) atmosphere. The resulting CC powders were stirred with 3 M HCl for 30 min, then washed with deionized (DI) water until the pH was neutral and oven-dried at 80 °C for 24 h. The final step involved particle size reduction by ball milling. All CC powders were milled under identical conditions, using 2 g of CC powder, 220 g of 5-mm zirconia milling balls, and 50 mL of DI water in 100 mL high-density polyethylene (HDPE) bottles. The bottles were rolled in a fixed direction at a constant rotational speed of 120 rpm for 30 min. The CC powders were designated as **NCCT** and **CCT**, referring to samples before and after washing with HCl and DI water, respectively, where **T** denotes the carbonization temperature.

CCT electrodes were prepared by mixing CCT powder with carbon black and PVDF in an 80:10:10 weight ratio, using 1 mL of NMP as the solvent, stirring the mixture, and allowing it to sit overnight. Then, 0.1 mL of the resulting slurry was dropped onto a $1 \times 1\text{ cm}^2$ graphite sheet and dried at 80 °C for 24 h.

2.3 Characterization

The thermal properties of the banana peels were tested using a simultaneous thermal analyzer (STA, STA 449 F5 Jupiter) at a heating rate of $10\text{ }^\circ\text{C} \cdot \text{min}^{-1}$ under a nitrogen atmosphere. A desktop scanning electron microscope (MiniSEM, SEC, SNE-4500 M), equipped with an energy-dispersive X-ray (EDX) detector, was employed to study morphologies and elemental composition. The crystal structures and impurity phases of the CC powders were examined using X-ray diffraction (XRD, PAN-alytical, EMPYREAN). Fourier transform infrared spectroscopy (FT-IR, Bruker, TENSOR27) was employed to identify surface functional groups of the carbon powders. The surface chemical states were further investigated using X-ray photoelectron spectroscopy (XPS, Kratos AXIS Supra+). Specific surface area and the porosity of carbon powders were analyzed using N_2 adsorption-desorption isotherms and the Brunauer-Emmett-Teller (BET) method (Micromeritics ASAP 2460, Version 3.01). The porosity of CCT powders was preliminarily estimated using the American Society for Testing and Materials (ASTM) international standard test method for determining the iodine number of activated carbon (ASTM D4607–86), as described in Equation (1):

$$\frac{X}{M} = \frac{A - (DF)(B)(S)}{M} \quad (1)$$

where $\frac{X}{M}$ is the amount of iodine adsorbed per gram of carbon ($\text{mg} \cdot \text{g}^{-1}$); A is the product of iodine normality and 6346.5, calculated as $(0.099 \times 6346.5) = 628.30$; B is the product of sodium thiosulfate normality and 126.93, calculated as $(0.105 \times 126.93) = 13.33$; S is the volume of sodium thiosulfate used (mL); and M is the mass of carbon (g), which was 0.2 g. DF is the dilution factor, defined as:

$$DF = \frac{I + H}{F} \quad (2)$$

where I is the volume of iodine solution (mL), H is the volume of 5% HCl (mL), and F is the volume of filtrate (mL). In this work, I = 50 mL, H = 5 mL resulting in $DF = (50 + 5)/25 = 2.2$.

The electrochemical properties of CCT electrodes were evaluated using cyclic voltammetry (CV), galvanostatic charge/discharge (GCD), and electrochemical impedance spectroscopy (EIS). These tests were conducted using a CS310 electrochemical workstation (Wuhan Corrtest Instruments Corp. Ltd., China) in a three-electrode mode. A CCT electrode served as the working electrode, Ag/AgCl was a reference electrode, and a platinum (Pt) plate functioned as a counter electrode. Three-electrode tests were performed in a 1 M H_2SO_4 electrolyte. Specific capacitance (C_s) of AC electrodes was calculated using Equations (3) and (4) from the respective GCD and CV techniques.

$$C_s = \frac{I\Delta t}{m\Delta V} \quad (\text{For GCD}) \quad (3)$$

$$C_s = \frac{\int IdV}{2mv\Delta V} \quad (\text{For CV}) \quad (4)$$

where $\int IdV$ is the integrated area under a CV curve, m is the mass of active material on the graphite sheet, and v is the scan rate. ΔV is the potential range (1.2V), I is the discharge current, and Δt is the discharge time.

The charge storage mechanism of a supercapacitor is generally governed by two primary processes: capacitive (surface-controlled, electric double-layer capacitance) and diffusion-controlled (pseudocapacitive or Faradaic redox) contributions. These mechanisms can be analyzed using Dunn's method, expressed by the power-law relationship:

$$i = av^b \quad (5)$$

where i is the current and v is the scan rate. The exponent b in the above equation typically ranges between 0.5 and 1. A b -value close to 1 indicates that charge storage is dominated by a surface-controlled capacitive process, whereas a b -value near 0.5 suggests a diffusion-controlled process (pseudocapacitive). The total CV current response at a given potential can be separated into capacitive and diffusion-controlled components using the following equation:

$$i(v) = k_1 v + k_2 v^{1/2} \quad (6)$$

where $k_1 v$ represents the capacitive (surface-controlled) contribution, and $k_2 v^{1/2}$ corresponds to the diffusion-controlled (Faradaic/intercalation) contribution.

3. Results and discussion

3.1 Physical and chemical properties of CCT powders

The thermogravimetric (TG) and derivative thermogravimetric (DTG) curves of banana peels are shown in Figure 1(a). The thermal behavior can be divided into three distinct zones. The first zone (25–150 °C) corresponds to moisture loss [2, 12] and accounts for approximately 13% of the total weight loss. The second zone (150–500 °C) exhibits multiple degradation peaks at approximately 188, 258, 297, and 377 °C, which are attributed to the thermal decomposition of polysaccharides (hemicellulose and cellulose) and lignin, respectively [12–14], and account for 57% of the total weight loss. The final zone (500–1100 °C) corresponds to the complete decomposition stage, with only 23–30% of the initial weight remaining. This stage is considered the optimal temperature range for carbonization, as it facilitates the formation of stable carbon structures. Therefore, carbonization temperatures between 500 and 1000 °C were selected for converting banana peels into carbon materials. Figure 1(b) presents the differential scanning calorimetry (DSC) profile of banana peels. An endothermic peak was observed around 70 °C, attributed to the evaporation of physically bound water. Above 130 °C, exothermic reactions become dominant, associated with the release of heat during the formation of aromatic compounds [14, 15].

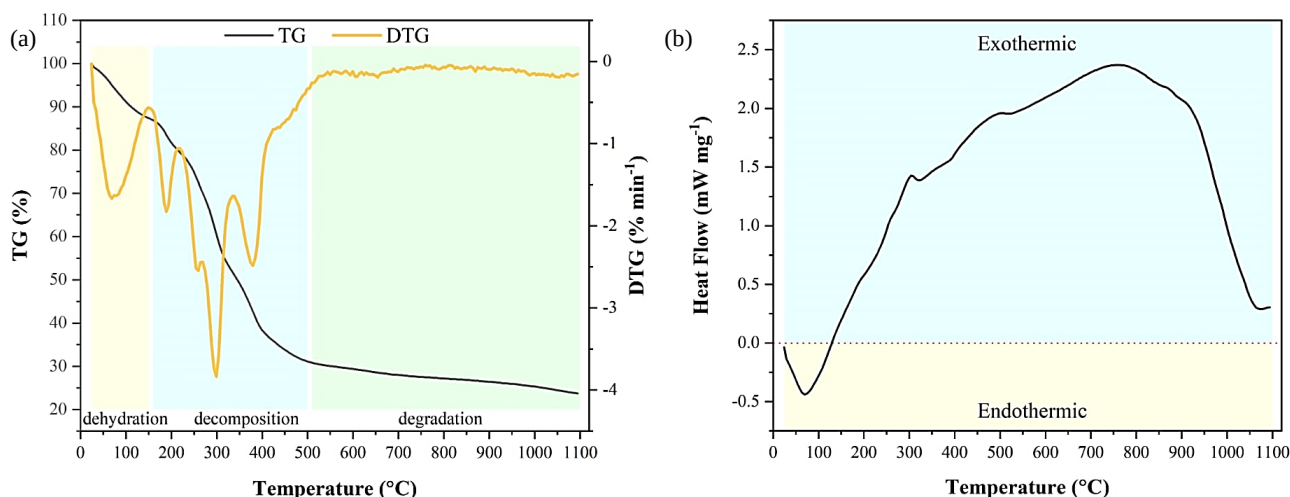


Figure 1 Thermal analysis of the banana peel precursor: (a) TG/DTG, and (b) DSC curve indicating endothermic and exothermic transitions during heating.

Figure 2(a) shows the XRD pattern of NCCT powders not washed with HCl and DI water. Distinct diffraction peaks were observed at 28° and 40°, corresponding to KCl (JCPDS No. 00-041-1476), and at 25.7°, 26.9°, 32.1°, 32.6°, and 41.3°, which are the main peaks of K₂CO₃·1.5H₂O (JCPDS No. 00-011-0655). These results indicate that potassium salts, such as oxides, carbonates, and chlorides, are the dominant crystalline phases in banana peel ash [16]. After washing with HCl and DI water, these potassium salts were entirely removed, with only carbon remaining, as shown in Figure 2(b). The washed CCT powders exhibit broad diffraction peaks at around 22° and 43°, which are characteristic of amorphous carbon (JCPDS No. 01-075-1621) [17]. In contrast, the raw banana peel shows broader peaks at approximately 16°, 21°, and 35°, which correspond to amorphous cellulose (JCPDS No. 03-0829) [18].

The FT-IR spectra of banana peels and all the tested CCT powders are shown in Figure 2(c). The banana peel and the CCT powders exhibit several absorption bands corresponding to various oxygen-containing functional groups. A broad band at 3400 cm⁻¹ is attributed to the stretching vibrations of hydroxyl (O-H) and amine (N-H) groups [18–20]. The peaks observed at 2920 cm⁻¹ and 2850 cm⁻¹ correspond to the stretching vibrations of aliphatic C-H bonds [18–20]. The absorption band observed at 1710–1720 cm⁻¹ is ascribed to C=O stretching vibrations, association with carboxylic groups (-COOH, -COOCH₃) [18–20]. Absorption in the region of 1640–1610 cm⁻¹ corresponds to skeletal vibrations of aromatic C=C bonds [18, 21]. The band at 1448 cm⁻¹ is attributed to symmetric vibrations of phenolic -COO- groups, originating from hemicellulose [22]. A peak at 1037 cm⁻¹ corresponds to C-O and C-C stretching vibrations, confirming the presence of hemicellulose, cellulose, and lignin components in the banana peels [22]. The band at 889 cm⁻¹ is associated with the N-H deformation of amines [20]. For the CCT powders, additional bands are observed at 1700–1720 cm⁻¹ corresponding to C=O stretching [23, 24], and the peak at 1560–1580 cm⁻¹ is ascribed to C=C bonds of aromatic rings [23, 24]. The absorption bands at 1080–1090 cm⁻¹ are attributed to C-O stretching [25] or C-O-C vibrations in alcohol, phenol, ether, or ester groups [26]. The absorption band appearing at approximately 850–860 cm⁻¹ can be ascribed to the C-O-H vibrations of quinone functional groups [27].

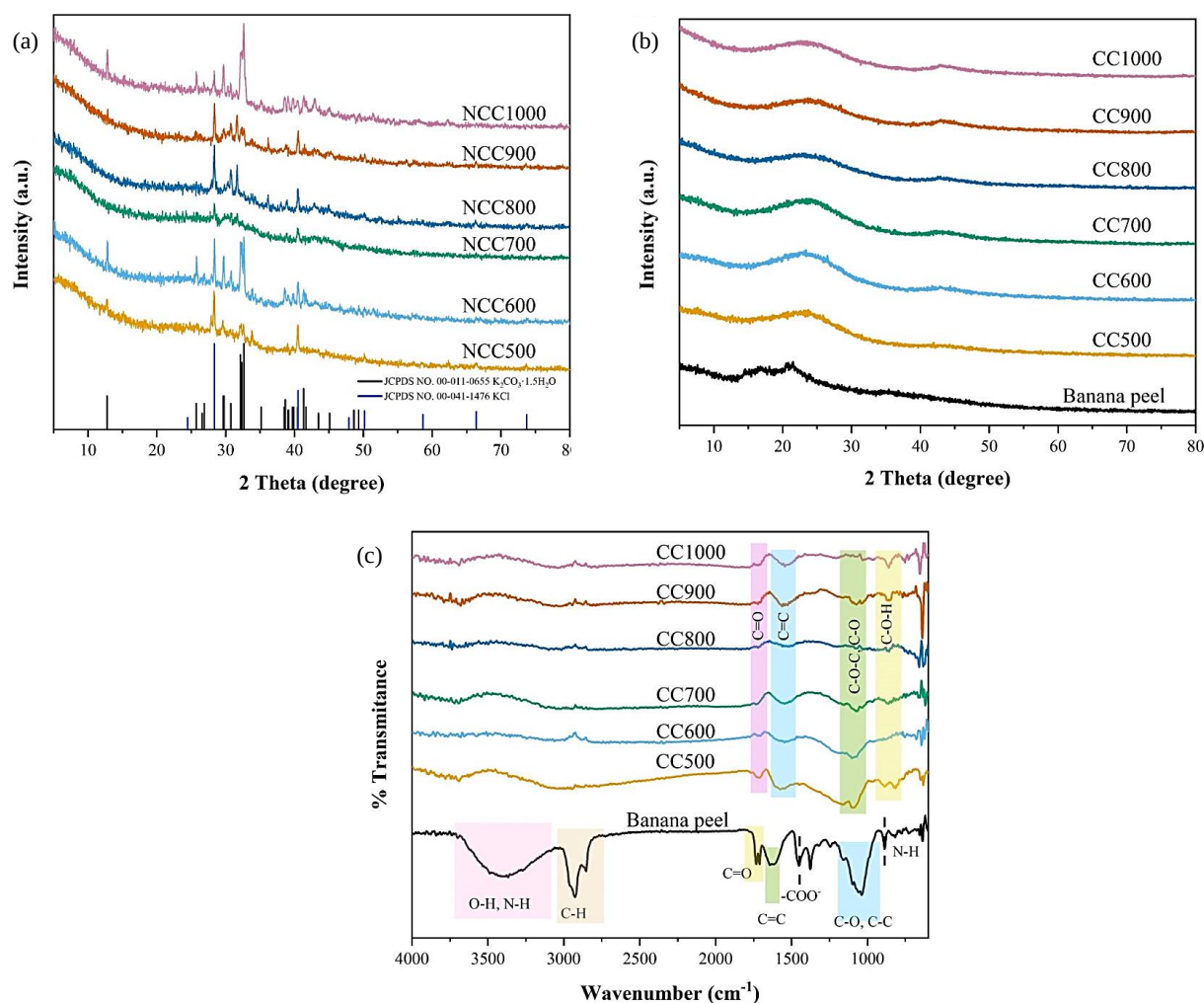


Figure 2 XRD patterns of (a) NCCT, (b) CCT powders, and (c) FT-IR results of banana peel and CCT powders prepared at different carbonization temperatures.

The elemental composition of dried banana peels, CCT powders, and NCC800 powder, obtained from EDX analysis, is summarized in Table 1. Dried banana peels contain 72.00% C, 24.22% O, and 2.44% K. After carbonization at 800 °C with no HCl washing (NCC800), the composition changes significantly to 47.84% C, 22.87% O, and 22.95% K. The decrease in carbon content is attributed to thermal decomposition of cellulose, hemicellulose, and lignin, which are the major carbon-containing components of biomass [12]. In contrast, inorganic species such as potassium are thermally stable and tend to remain in the solid residue after pyrolysis, leading to their increased proportion after carbonization. During high-temperature pyrolysis, potassium species may interact with biomass and/or gases, forming KCl and potassium carbonate species (e.g., $K_2CO_3 \cdot xH_2O$) [28]. The XRD spectra in Figure 2(b) display the presence of the KCl and $K_2CO_3 \cdot 1.5H_2O$ phases in NCC800. In the CCT powders (HCl-washed sample), carbon is the dominant element, accounting for more than 90% of its total composition, followed by oxygen at approximately 5–7%. Other elements are present only in trace amounts (<1%). These are commonly found in acid-treated biomass-derived carbons [29]. XRD analysis of CCT powders in Figure 2(b) shows an amorphous carbon phase, implying effective removal of inorganic compounds from powders.

Table 1 Elemental composition of banana peels, CCT powders, and NCC800 powder.

Sample	Elemental (At%)								
	C	O	Mg	Si	P	Cl	Ca	K	S
Banana peel	72.00	24.22	0.93	0.14	0.13	0.14	-	2.44	-
CC500	91.21	7.32	0.46	0.31	0.43	0.14	0.13	-	-
CC600	91.60	5.58	0.26	1.85	0.23	0.18	-	0.21	0.009
CC700	92.02	6.38	0.47	0.27	0.52	0.10	0.24	-	-
CC800	92.19	5.78	0.58	0.41	0.65	0.11	0.30	-	-
CC900	92.07	4.92	0.36	0.82	0.62	0.36	0.27	0.57	-
CC1000	93.23	5.48	0.14	0.16	0.31	0.15	0.24	0.28	-
NCC800	47.84	22.87	1.34	4.05	0.30	0.65	-	22.95	-

The surface morphology of the CCT powders was examined using SEM at a 1000X magnification, and the resulting images are shown in Figure 3. CCT powders exhibited numerous porous structures having diameters of approximately $32.7 \pm 2.4 \mu m$, whereas the dried banana peel sample (Figure 3(g)) shows closed cell walls and less-developed pores. The morphology of the NCC800 sample (Figure 3(h)) exhibited a porous structure, similar to that of the CCT samples.

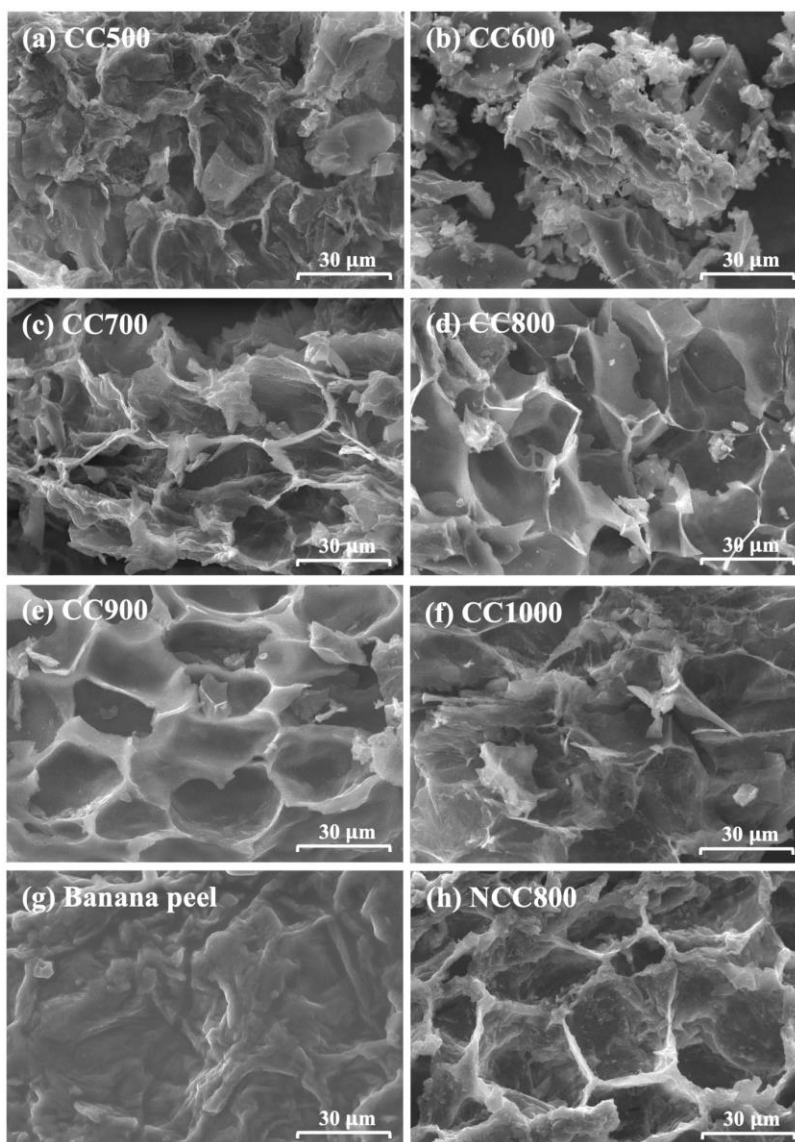


Figure 3 SEM images of (a–f) CCT powders prepared at different carbonization temperatures, (g) raw banana peel, and (h) NCC800 powder.

The porosity of the CCT powders, determined by the iodine adsorption method, is presented in Table 2. The iodine adsorption value increased gradually from 500 to 800 °C, then decreased slightly at 900 °C, and declined significantly at 1000 °C. Among the samples, CC800 exhibited the highest iodine adsorption ($485.80 \text{ mg} \cdot \text{g}^{-1}$), while CC500 showed the lowest value ($-10.42 \text{ mg} \cdot \text{g}^{-1}$). The increase in iodine adsorption values corresponds to greater surface area. This suggests that the CC800 sample has the highest surface area. Higher temperatures (900 and 1000 °C) reduced iodine absorption values, likely due to excessive thermal activation collapsing the pore structure. The negative iodine adsorption value observed for the CC500 powder is likely due to experimental limitations associated with a reduced iodine solution volume. Specifically, reducing the iodine solution from 100 mL to 50 mL decreases the total iodine available for adsorption, resulting in very low iodine uptake by the CC500 powder. The calculated value is highly sensitive to minor titration deviations, leading to negative values. The iodine value trend is consistent with the BET analysis.

Table 2 Iodine adsorption values and specific capacitance (C_s) of CCT powders, calculated from CV and GCD data.

Sample	Iodine adsorption ($\text{mg} \cdot \text{g}^{-1}$)	C_s at $5 \text{ mV} \cdot \text{s}^{-1}$ ($\text{F} \cdot \text{g}^{-1}$)	C_s at $0.5 \text{ A} \cdot \text{g}^{-1}$ ($\text{F} \cdot \text{g}^{-1}$)
CC500	-10.42	72.84	87.55
CC600	194.20	102.28	129.79
CC700	150.04	83.52	119.75
CC800	485.80	108.47	169.26
CC900	471.44	114.81	153.86
CC1000	325.09	57.08	60.61

To accurately determine the surface area and pore characteristics, all tested samples were further analyzed using nitrogen adsorption-desorption measurements. The obtained parameters, including the specific surface area (S_{BET}), micropore surface area (S_{micro}), mesopore surface area (S_{meso}), total pore volume (V_{tot}), micropore volume (V_{micro}), mesopore volume (V_{meso}), and average pore diameter (D_{avg}), are summarized in Table 3. The corresponding adsorption-desorption isotherm curves and pore size distribution are

presented in Figure 4. The adsorption-desorption isotherm curves of all derived carbons can be classified as Type I (Figure 4(a)), which is a typical characteristic of microporous adsorbents, according to the IUPAC classification [30]. Their H₄-type hysteresis loops indicate a low adsorption capacity and narrow, slit-like pores. Based on the isothermal profiles and hysteresis behavior, all tested CCT powders exhibited predominantly microporous structures. These pores were generated by the release of gaseous products, such as CO₂, H₂O, and CO, during the thermal decomposition of moisture and lignocellulosic components, as described by Equations 7–10 [2, 31].



The released gases reacted with the carbon matrix, removing carbon atoms and thereby creating open spaces and pores. As shown in Figure 4(a), CC800 exhibits a higher adsorption value than CC500–CC700 powders (lower carbonization temperatures) and NCC800 powders, indicating that the development of porosity becomes more pronounced at elevated carbonization temperatures, resulting in more N₂ accessing sites (see Table 3). However, higher carbonization temperatures (900 and 1000 °C) decreased the adsorption capacity. This should be due to partial pore collapse or structural shrinkage. CC800 powder exhibits the highest specific surface area (800.846 m²·g⁻¹). However, NCC800 exhibits the lowest adsorption capacity, which can be attributed to residual KCl and K₂CO₃·1.5H₂O compounds, hindering pore development. The pore size distribution obtained from the Barrett-Joyner-Halenda (BJH) model revealed that the pore volume of the CCT samples increased with carbonization temperature, reaching the highest value at 800 °C (0.362 cm³·g⁻¹). Higher carbonization temperatures, 900 and 1000 °C, resulted in decreased pore volume. Notably, all tested CCT samples exhibited significantly higher pore volumes than NCC800 (0.051 cm³·g⁻¹). This result indicates that the removal of potassium salts and other inorganic species during acid washing promoted pore development, as supported by SEM observations (Figure 3). The variation in pore volume follows the BET surface area trend, and the nitrogen adsorption results (Table 3), which is consistent with the iodine adsorption values (Table 2).

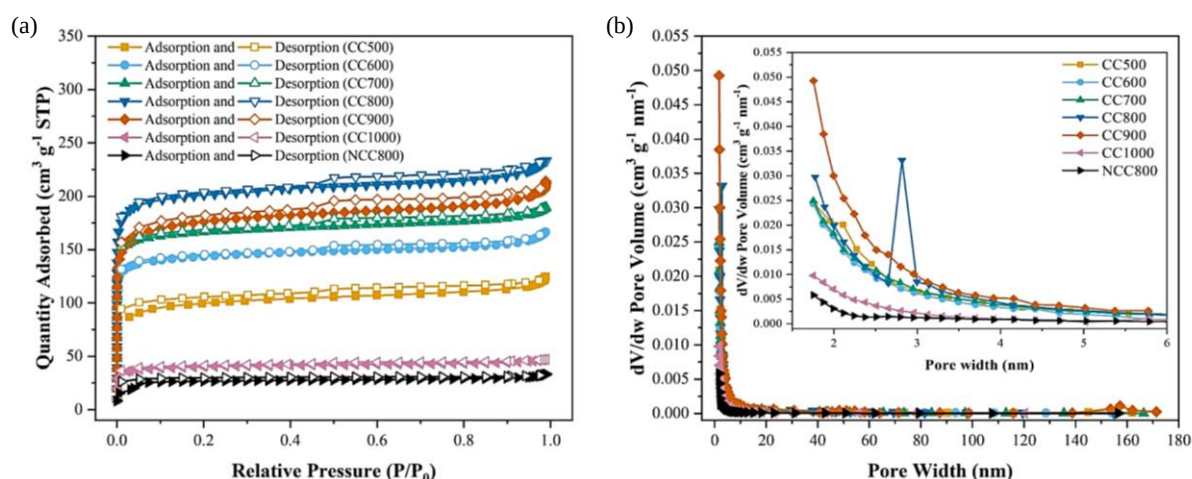


Figure 4 (a) N₂ adsorption-desorption of CCT powders and NCC800 powder, (b) pore size distribution of CCT powders, and NCC800 powder.

Table 3 Surface area and pore volume properties, including specific surface area (S_{BET}), micropore surface area (S_{micro}), mesopore surface area (S_{meso}), total pore volume (V_{tot}), micropore volume (V_{micro}), mesopore volume (V_{meso}), and average pore diameter (D_{avg}) of CCT powders, and NCC800 powder.

Sample	S_{BET} (m ² ·g ⁻¹)	S_{micro} (m ² ·g ⁻¹)	S_{meso} (m ² ·g ⁻¹)	V_{tot} (cm ³ ·g ⁻¹)	V_{micro} (cm ³ ·g ⁻¹)	V_{meso} (cm ³ ·g ⁻¹)	D_{avg} (nm)
CC500	382.403	358.061	24.342	0.193	0.148	0.104	1.936
CC600	571.690	547.490	24.200	0.258	0.215	0.166	1.744
CC700	665.061	636.869	28.192	0.294	0.248	0.197	1.730
CC800	800.846	778.572	22.274	0.362	0.310	0.240	1.771
CC900	684.595	644.882	39.714	0.332	0.260	0.184	1.859
CC1000	156.881	150.263	6.619	0.073	0.061	0.047	1.826
NCC800	103.398	97.624	5.773	0.051	0.039	0.012	1.907

3.2 Electrochemical properties of CCT electrodes

The GCD curves of the CCT electrodes at a current density of 0.5 A·g⁻¹ are shown in Figure 5(a). All tested samples exhibited nearly triangular GCD profiles, which are characteristic of electric double-layer capacitors. The GCD curves had a distinct plateau around 0.5–0.6 V with associated Faradaic redox reactions on these electrodes. The specific capacitance values calculated from the GCD curves using Equation (3) are summarized in Table 2. Among them, the CC800 electrode exhibits the longest discharge times and the highest specific capacitance, 169.26 F·g⁻¹. This is attributed to its relatively large specific surface area (800.846 m²·g⁻¹). The

specific capacitance of all samples in Figure 5(b) decreases with increasing current density. This occurs since, at low current densities, the charge-discharge process occurs relatively slowly, allowing sufficient time for ions to diffuse into the porous structure of the electrode, resulting in higher specific capacitance. In contrast, at higher current densities, the charge-discharge process becomes rapid, limiting ion diffusion into the pores and causing incomplete charge storage. This behavior is typical of supercapacitor systems [32]. Figure 5(c) shows the CV curves of all tested CCT electrodes measured at a $5 \text{ mV} \cdot \text{s}^{-1}$ scan rate. The curves exhibit nearly rectangular shapes with distinct redox peaks, indicating the coexistence of electric double-layer capacitance and pseudocapacitive behavior. The oxidation peaks appear at around $0.6\text{--}0.7 \text{ V}$, while the reduction peaks occur at $0.4\text{--}0.5 \text{ V}$. These potentials align well with the plateau region ($0.5\text{--}0.6 \text{ V}$) in the GCD curves, confirming the presence of reversible redox reactions on the electrode surface. The specific capacitance values calculated from the CV curves, according to Equation (4), are summarized in Table 2. A slight difference in the capacitance trend is observed between the CV and GCD results. The C_s from CV measurements at $5 \text{ mV} \cdot \text{s}^{-1}$ of CC900 is a slightly higher capacitance ($114.81 \text{ F} \cdot \text{g}^{-1}$) than CC800 ($108.47 \text{ F} \cdot \text{g}^{-1}$). However, the C_s of the CC800 electrode from the GCD measurement at $0.5 \text{ A} \cdot \text{g}^{-1}$ is the highest value ($169.26 \text{ F} \cdot \text{g}^{-1}$), exceeding that of CC900 ($153.86 \text{ F} \cdot \text{g}^{-1}$). This discrepancy can be attributed to the different charge-storage characteristics captured by the two electrochemical techniques. CV measurements are more sensitive to surface-controlled pseudocapacitive reactions, whereas GCD measurements better reflect ion diffusion and charge-discharge behavior within the porous structure under constant current conditions. Thus, the observed redox behavior of the CV curves likely arises from surface functional groups, including quinone species, pyrone derivatives, and other oxygen-containing groups [33–35]. The presence of these functionalities on the carbon surface is supported by the FT-IR results (Figure 2(c)), which reveals characteristic vibrations related to $\text{C}=\text{O}$ and other oxygen-containing functional groups. These functionalities undergo reversible Faradaic reactions, thereby contributing to pseudocapacitive behavior by storing and releasing charge, as shown in Figure 5(d). The pseudocapacitive mechanism involves the oxidation of hydroquinone and hydroxyl groups on the aromatic rings into quinone and carbonyl groups during charging. Upon discharge, the carbon electrode gains electrons (e^-), facilitating the insertion of protons (H^+) from the electrolyte and reducing quinone and carbonyl groups to hydroquinone and hydroxyl groups [33–35].

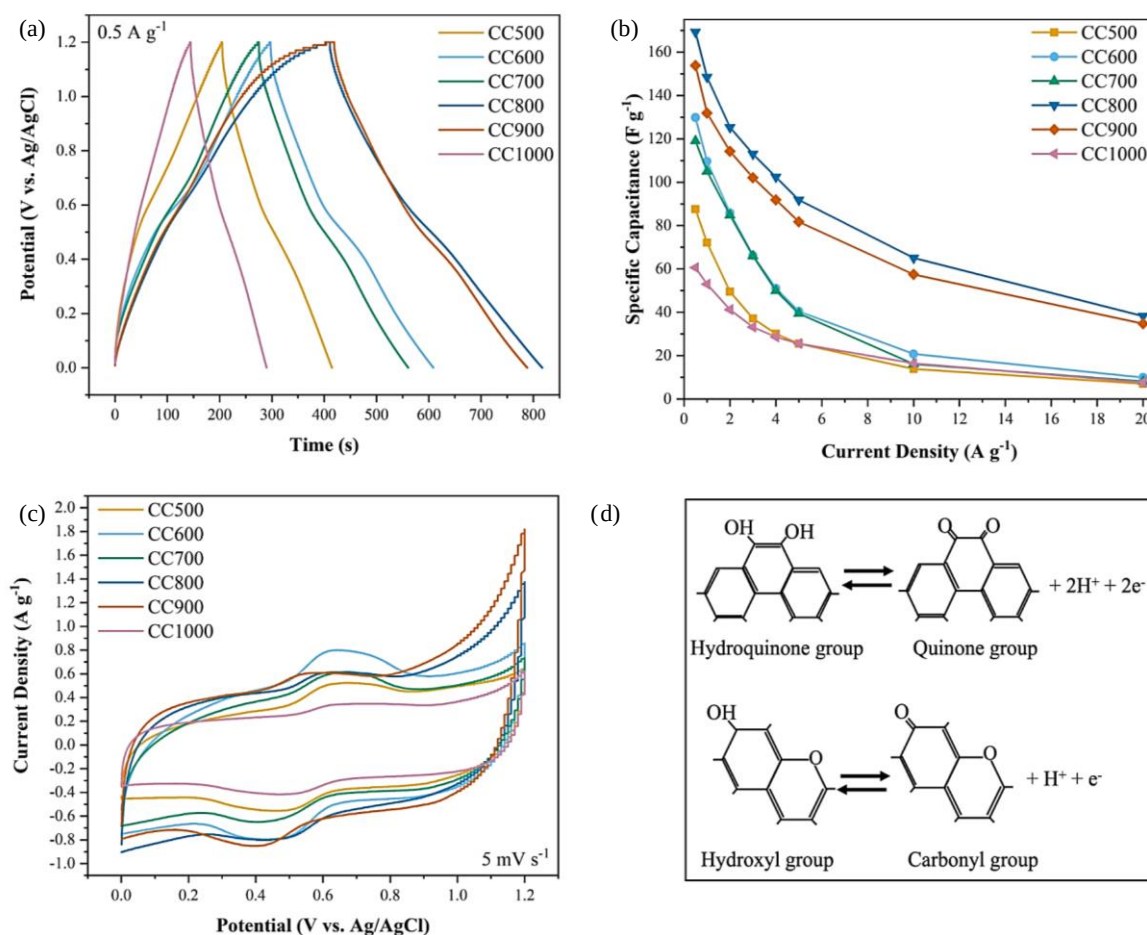


Figure 5 Electrochemical characterization of CCT electrodes: (a) GCD curves at a current density of $0.5 \text{ A} \cdot \text{g}^{-1}$, (b) specific capacitances at different current densities, (c) CV curves at a $5 \text{ mV} \cdot \text{s}^{-1}$ scan rate, and (d) schematic of the reaction on the carbon surface in an acidic electrolyte.

To further verify the redox transformation of quinone-related species after the charge-discharge process, XPS analysis was conducted on the CC800 electrode under four representative conditions: (1) pristine electrodes, (2) electrodes after soaking in a $1 \text{ M H}_2\text{SO}_4$ electrolyte, (3) electrodes charged to 1.2 V , and (4) electrodes discharged to 0 V . The XPS survey spectra in Figure 6(a) show C, O, and F. The F signal should originate from the $-\text{CF}_2$ groups of the PVDF binder. The high-resolution $\text{C} 1\text{s}$ spectrum of the pristine CC800 electrode was deconvoluted into four subpeaks at binding energies of 284.98 , 286.40 , 288.82 , and 291.29 eV , respectively corresponding to $\text{C}=\text{C}/\text{C}-\text{C}$, $\text{C}-\text{O}$, $\text{C}=\text{O}$, and $-\text{CF}_2$ bonds [36–38], as shown in Figure 6(b). To evaluate the evolution of quinone-related functional groups during the electrochemical process, the $\text{C}-\text{O}/\text{C}=\text{O}$ peak area ratio was calculated. The pristine CC800 electrode has an $8.73 \text{ C}-\text{O}/\text{C}=\text{O}$ ratio. After soaking in the H_2SO_4 electrolyte, the $\text{C}-\text{O}/\text{C}=\text{O}$ ratio slightly increased to 8.86 , indicating a minor

surface interaction with the electrolyte. Upon charging to 1.2 V, the C–O/C=O ratio decreased to 7.29. This suggests that the hydroquinone and hydroxyl groups are oxidized to quinone and carbonyl species. In contrast, when discharged to 0 V, the C–O/C=O ratio significantly increased to 11.35. This indicates the reduction of quinone and carbonyl groups back to hydroquinone and hydroxyl functionalities, as illustrated in Figure 5(d). A similar trend is observed in the O 1s spectra. O 1s spectra were deconvoluted into four subpeaks at binding energies of 531.53, 532.50, 533.50, and 535.15 eV, corresponding to O=C, O–C, O–H, and adsorbed H₂O species, respectively. The O–C/O=C peak area ratio shows a variation consistent with that of the C–O/C=O ratio, as summarized in Table 4. These results clearly show reversible transformations between hydroquinone/hydroxyl and quinone/carbonyl groups during charge-discharge. Thus, these XPS results confirm that quinone-related surface functional groups play an important role in the pseudocapacitive charge-storage mechanism of the carbon electrode.

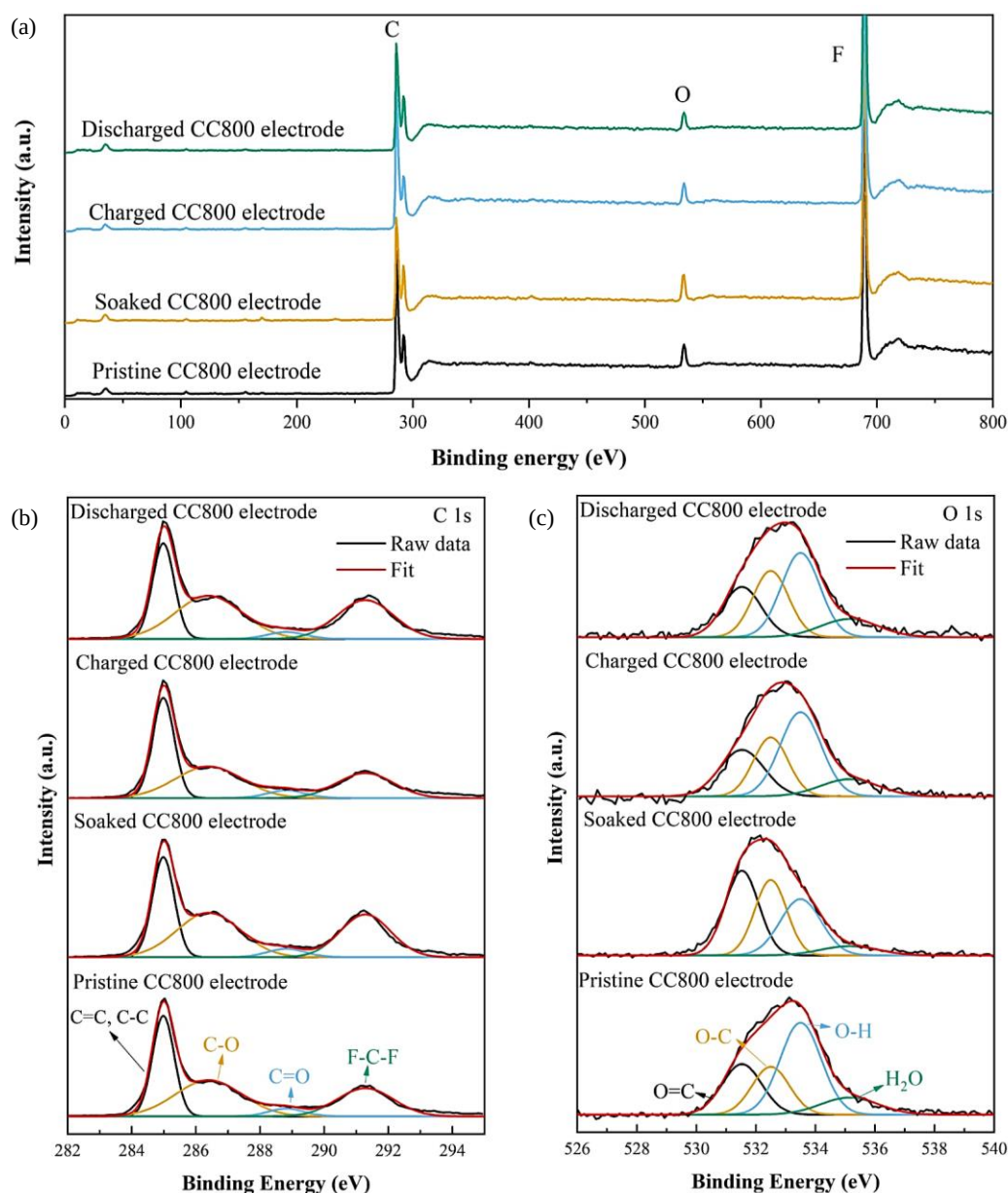


Figure 6 (a) Survey XPS spectra of the CC800 electrode at different states: pristine electrode, after soaking in an H₂SO₄ electrolyte, after charging to 1.2 V, and after discharging to 0 V. High-resolution XPS spectra of (b) C 1s, and (c) O 1s for the CC800 electrode under the corresponding conditions.

Table 4 Integrated peak area ratio of C–O/C=O from the C 1s, and O–C/O=C from the O 1s spectrum obtained from the XPS analysis of the electrode.

State	C–O/C=O (C 1s)	O–C/O=C (O 1s)
Pristine CC800 electrode	8.73	0.89
Soaked CC800 electrode	8.86	0.84
Charged CC800 electrode	7.29	0.80
Discharged CC800 electrode	11.35	1.22

Additionally, the relative contributions of electric double-layer capacitance and pseudocapacitance of each carbon electrode were quantitatively evaluated using Dunn's method. The CV curve of all electrodes was evaluated according to Equation (5), as shown in Figure 7. The calculated b -values for the reduction peak for all tested samples are plotted in Figure 7(a) and listed in Table 5. The obtained b -values for all tested electrodes at a $5 \text{ mV}\cdot\text{s}^{-1}$ scan rate fall within the ~ 0.57 – 0.98 range, indicating the coexistence of diffusion-controlled (redox) and surface-controlled (capacitive) mechanisms. Low-temperature carbonized samples (CC500, CC600, and CC700) exhibit b -values of approximately ~ 0.6 , which is close to 0.5 , suggesting a dominant diffusion-controlled process. High carbonization temperatures (CC800–CC1000) gradually increased the b -value, reaching a maximum of 0.98 for CC1000. This indicates a shift toward capacitive-dominated behavior. Evolution from diffusion-controlled to capacitive-controlled behavior should be attributed to the gradual decomposition of oxygen-containing functional groups at elevated temperatures [39]. Andreas and Conway [34] reported that the reduction of oxygen-containing functional groups reduces the contribution of Faradaic (diffusion-controlled) reactions. The FT-IR results (Figure 2(c)) show that the intensity of oxygen-containing functional groups (e.g., C=O and C-O bands) decreases with increasing carbonization temperature. The relative contributions of capacitive and diffusion-control for all samples, calculated using Equation (6), are presented in Figure 7(b). All tested samples indicate both mechanisms. Figure 7(c) shows that increasing the scan rate for the CC800 electrode increases the surface-controlled contribution but reduces the diffusion-controlled one. This behavior can be attributed to the limited ion diffusion and insufficient time for redox reactions at higher scan rates, which favor surface-controlled charge storage, as illustrated in Figure 7(d).

Table 5 Calculated b -values of CCT electrodes obtained from the $\log(i)$ – $\log(v)$ plots based on CV measurements, representing the oxidation and reduction peaks and indicating the charge-storage kinetics.

Sample	b -values	Surface Contribution at $5 \text{ mV}\cdot\text{s}^{-1}$ (%)	Diffusion Contribution at $5 \text{ mV}\cdot\text{s}^{-1}$ (%)
CC500	0.63	6.87	93.13
CC600	0.58	3.65	96.35
CC700	0.57	6.77	93.23
CC800	0.72	23.39	76.61
CC900	0.76	21.90	78.10
CC1000	0.98	65.06	34.94

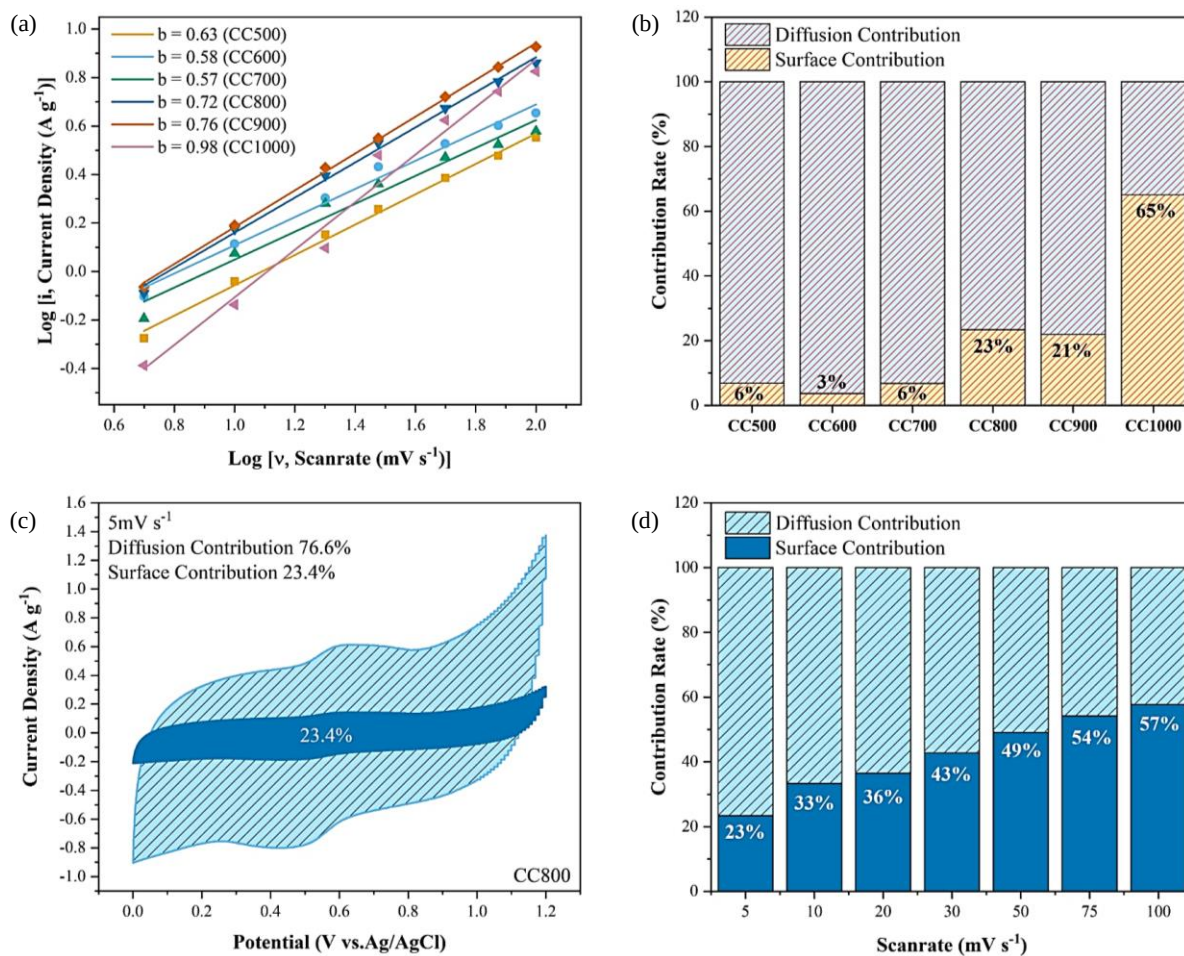


Figure 7 (a) Determination of b -values from the relationship between $\log(i)$ and $\log(v)$ for the tested CCT electrodes. (b) Relative contributions of diffusion-controlled and surface-controlled processes for all CCT electrodes at a $5 \text{ mV}\cdot\text{s}^{-1}$ scan rate. (c) Separation of the diffusion-controlled and capacitive current contributions for the CC800 electrode at $5 \text{ mV}\cdot\text{s}^{-1}$. (d) Variation of diffusion-controlled and surface-controlled contributions for the CC800 electrode at various scan rates.

The EIS of all electrodes measured in a three-electrode configuration is presented in the Nyquist plots shown in Figure 8(a). All samples exhibit inclined lines, representing Warburg-type impedance via ion diffusion within the porous electrode [40, 41]. This behavior is commonly observed in porous carbon electrodes. The equivalent circuit model shown in Figure 8(b) was employed to extract the series resistance (R_s), charge transfer resistance (R_{ct}), and Warburg impedance (W) of the electrodes, as summarized in Table 6. The R_s values for all tested CCT electrodes range from 1.0–1.2 Ω , suggesting similar interfacial contact resistance between the active materials and the substrate. The CC800 sample exhibits the lowest R_{ct} value (1.5 Ω), demonstrating its superior charge-transfer kinetics and lower interfacial resistance resulting in the high specific capacitance. The CC1000 sample has the highest R_{ct} value (12.26 Ω), resulting in the lowest specific capacitance (60.61 $F \cdot g^{-1}$) among these electrodes. These results suggest that high porosity reduces the charge-transfer resistance and improves specific capacitance.

A comparison of the surface area and electrochemical performance of biomass-derived carbon electrodes reported in the literature is summarized in Table 7. The CC800 electrode prepared in this work has a specific capacitance of 169.29 $F \cdot g^{-1}$ at 0.5 $A \cdot g^{-1}$ in 1 M H_2SO_4 , with a specific surface area of 800.846 $m^2 \cdot g^{-1}$, comparable to the previously reported carbon materials evaluated in the same electrolyte (1 M H_2SO_4). For example, rice husk-derived carbon had a surface area of 156.1 $m^2 \cdot g^{-1}$ and delivered a C_s of 113.24 $F \cdot g^{-1}$. Paper flower-derived carbon exhibited a C_s value of 118 $F \cdot g^{-1}$ with a large surface area, 1801 $m^2 \cdot g^{-1}$. Purple corncob-derived carbon showed a higher capacitance, 195 $F \cdot g^{-1}$, with a 728 $m^2 \cdot g^{-1}$ surface area at a 0.5 $A \cdot g^{-1}$ current density. These results show that the banana peel-derived carbon synthesized via a self-activation process delivers promising electrochemical properties.

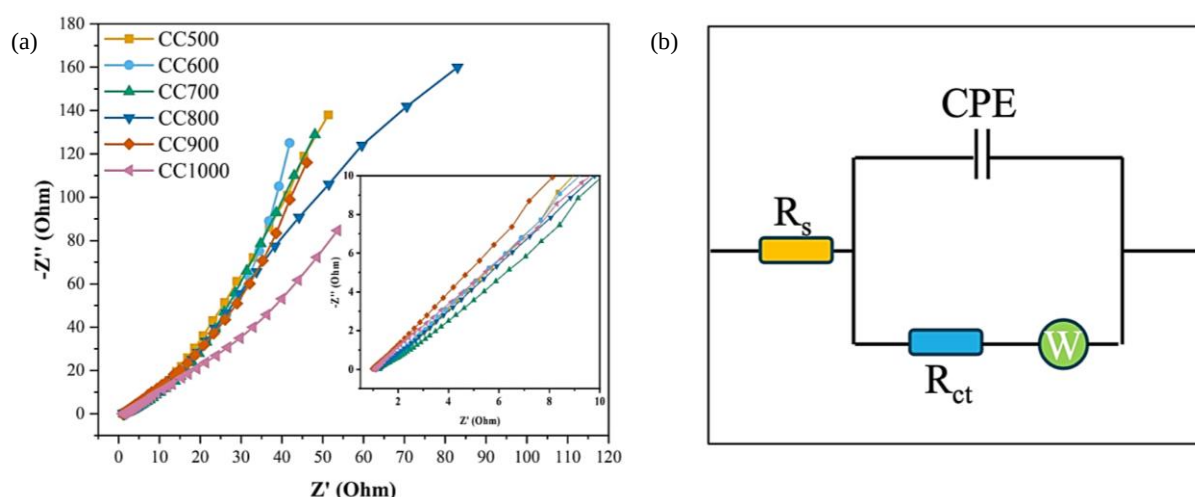


Figure 8 (a) Nyquist plots of all tested CCT electrodes, and (b) equivalent circuit model for fitting EIS data.

Table 6 EIS fitting parameters of all tested CCT electrodes.

Sample	R_s (Ω)	R_{ct} (Ω)	CPE-T (F)	CPE-P	W-R (Ω)
CC500	1.26	2.50	0.024	0.61	65.85
CC600	1.14	2.50	0.023	0.61	88.76
CC700	1.29	2.93	0.021	0.57	85.63
CC800	1.11	1.51	0.027	0.57	62.78
CC900	1.00	2.91	0.029	0.65	124.54
CC1000	1.06	12.26	0.034	0.59	313.59

Table 7 Comparison of the carbon properties and specific capacitance (C_s) of carbon electrodes derived from various biomass sources.

Biomass	Synthesis method	S_{BET} ($m^2 \cdot g^{-1}$)	Electrolyte	Test condition	C_s ($F \cdot g^{-1}$)	Ref.
Cabbage	Self-activated at 800 $^{\circ}C$	1146.51	6 M KOH	0.5 $A \cdot g^{-1}$	114.47	[2]
Corn stalks	KOH activation at 800 $^{\circ}C$	1724.64	6 M KOH	0.1 $A \cdot g^{-1}$	103	[42]
Rice husk	KOH activation at 600 $^{\circ}C$	156.1	1 M H_2SO_4	2 mV s^{-1}	113.24	[43]
Paper flower	$ZnCl_2$ activation at 800 $^{\circ}C$	1801	1 M H_2SO_4	1 $A \cdot g^{-1}$	118	[44]
Purple corncob	KOH activation at 700 $^{\circ}C$	728	1 M H_2SO_4	0.5 $A \cdot g^{-1}$	195	[45]
Banana peel	Self-activated at 800 $^{\circ}C$	800.846	1 M H_2SO_4	0.5 $A \cdot g^{-1}$	169.26	This work

4. Conclusions

Activated carbon derived from banana peels was successfully synthesized via a one-step carbonization process without oxidizing gases or additional chemical activators. The sample carbonized at 800 $^{\circ}C$ (CC800) exhibited the highest porosity, with an iodine adsorption value of 485.80 $mg \cdot g^{-1}$ and a BET surface area of 800.846 $m^2 \cdot g^{-1}$, as determined by N_2 adsorption analysis. In a 1 M H_2SO_4

electrolyte, CC800 achieved a maximum specific capacitance, $169.26 \text{ F} \cdot \text{g}^{-1}$, at a $0.5 \text{ A} \cdot \text{g}^{-1}$ current density. Furthermore, the presence of well-defined redox peaks under all tested conditions indicates the involvement of reversible Faradaic reactions between quinone/carbonyl functional groups on the carbon surface and hydrogen ions (H^+) in the electrolyte. This interaction enhances the material's overall pseudocapacitive behavior, as confirmed by XPS and quantitative analysis of capacitive and diffusion-controlled contributions using the power-law relationship and Dunn's method. The coexistence of electric double-layer capacitance and pseudocapacitive mechanisms contributes to the material's competitive electrochemical performance compared with chemically activated carbons. This simple, sustainable, and cost-effective approach demonstrates significant potential for converting agricultural waste into high-performance electrode materials for supercapacitor applications.

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