

Article

Coin-Cell Electric Double-Layer Capacitors with African Palm Kernel Activated Carbon Under Series and Parallel Connection

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Abstract

The growing demand for efficient and sustainable energy storage has intensified interest in green materials known for their high-power density. In this work, we evaluated the electrochemical and electrical performance of coin-cell supercapacitors with activated carbon electrodes from palm kernel shell. Two activated carbons were obtained using KOH and ZnCl₂ as activating agents at 700 °C and then superficially modified with nitric acid. The KOH-activated carbon electrodes showed the highest specific surface area (1181 m² g^{−1}) and the best electrochemical behavior, reaching an average gravimetric capacitance of 56. ± 9.2 F g^{−1}. The coins were characterized electrically by series and parallel arrangements, yielding specific energy and specific power densities of 2.6 Wh kg^{−1} and 475 W kg^{−1}, and 1.8 Wh kg^{−1} and 353 W kg^{−1}, at 0.001 A and 0.75 V for parallel and series arrangements, respectively.

Keywords: ultracaps; storage energy; carbonaceous materials



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1. Introduction

The use of renewable energy sources such as solar and wind has driven the development of energy storage systems (ESS) with features that reduce the risk of power outages during adverse weather conditions or allow excess stored energy to be injected into the power grid during peak demand. This improves grid stability, facilitating the seamless integration of renewable energy into existing energy infrastructure [1]. According to Rana et al. [2], an energy storage system can store electrical energy in different forms. ESS can be classified into five categories: mechanical, chemical, electrical, electrochemical, and thermal energy storage systems. Among these categories, ESS can store electrical energy as an electric or magnetic field. The former type of storage system can hold a significant amount of energy for short-term usage [2]. Supercapacitors fall within this category.

In contrast to lithium-ion batteries, supercapacitors do not exhibit high energy densities, which are typically in the range of 2–10 Wh kg^{−1}, with practical commercial values

commonly reported around 3–5 Wh kg^{−1} [3,4]. However, supercapacitors are characterized by significantly higher power densities, often exceeding 10–15 kW kg^{−1} and, in some cases, reaching above 20 kW kg^{−1}, enabling extremely fast charge and discharge processes [3,5]. Moreover, their operational lifetime largely surpasses that of lithium-ion batteries, with cycle life commonly approaching 10⁵–10⁶ charge–discharge cycles, compared to approximately 10³–5 × 10³ cycles for conventional lithium-ion technologies [4,6]. Owing to these characteristics, supercapacitors offer clear advantages in applications that demand high power, rapid energy exchange, and long-term durability, such as regenerative braking energy recovery in railway systems, short-term power buffering, and frequency and power fluctuation compensation in electrical power systems, where conventional battery-based storage may suffer from accelerated degradation.

Based on the charge-storage mechanism, supercapacitors can be classified into three types: electric double-layer capacitors (EDLCs), pseudocapacitors (PCs), and hybrid supercapacitors (HSCs). Electric double-layer capacitors (EDLC) are non-dielectric devices that store energy electrostatically. Charge storage in EDLC is governed by the adsorption of electrolyte ions on the electrically conducting electrode surface, which has a larger surface area and porosity. Pseudocapacitors consist of electrodes, a separator, a current collector, and an electrolyte with metal oxide/conduction polymers. Pseudocapacitors store electric charge through Faradaic processes involving rapid, reversible redox reactions at or near the electrode surface. In hybrid capacitors, the two electrodes employ distinct charge-storage mechanisms: capacitive and Faradaic mechanisms [3,4].

At the local level, a solution based on ultracapacitors has been implemented in the Medellín Metro system to compensate for reactive power on the 1500 V DC traction bus supplying the trains. This real-world application, reported in the literature, demonstrates the feasibility of ultracapacitor-based energy storage in railway traction systems. The system employs 16 ultracapacitor modules rated at 63 F and 125 V from Maxwell Technologies, arranged in a configuration of eight modules in series with two parallel branches, resulting in an equivalent capacitance of 15.75 F. This arrangement provides a maximum energy storage capacity of approximately 2.18 kWh while enabling a high-power capability of up to 220 kW, which is particularly advantageous for fast-response applications such as reactive power compensation, DC bus voltage stabilization, and dynamic support in electric traction systems [5].

Research on supercapacitors has involved a range of electrode materials. An ideal electrode material should possess high electrical conductivity, a larger electrochemically active surface area, higher electrochemical and thermal stability, greater surface wettability, and be cost-effective [6]. In this context, carbon-based electrodes, particularly activated carbons, provide a natural link between supercapacitor technology and sustainable material development, as their textural properties and surface chemistry can be tailored through activation and post-treatment processes. Agricultural waste is one of the most widely used raw materials for carbon electrode production due to its low cost. These materials are transformed into activated carbons and modified to obtain the desired characteristics. The activation process increases the surface area and the incorporation of heteroatoms such as Nitrogen (N) or Sulfur (S) into the molecular structure, whether from the natural presence of the biomass or introduced during treatment processes, can increase the active sites, further increase the electrical conductivity, and improve the wettability of the carbon materials and the electrolyte. This ultimately results in better electrochemical performance in supercapacitor applications [7].

In Colombia, palm oil is one of the most important crops. According to Fedepalma (the National Federation of Oil Palm Growers), Colombia is the largest producer of palm oil in America and the fourth largest in the world [8]. The waste from this crop has been

explored as a potential raw material for supercapacitor electrodes. Misnon et al. [9] obtained electrodes by physically (pyrolysis at 500 °C followed by steam activation) and chemically (pyrolysis at 500 °C followed by KOH activation) activating Palm kernel shells (PKS). Supercapacitors, using the activated carbons and three different electrolytes, 1 M Na₂SO₄, 6 M KOH, and 1 M H₂SO₄, were assembled in coin cells (CR2032). The Energy density (E_d) of SSCs decreased according to the following trend: neutral (1 M Na₂SO₄) > alkaline (6 M KOH) > acidic (1 M H₂SO₄). The physically activated carbon electrode showed the highest E_d of 7.4 Wh kg⁻¹ at a Power density (P_d) of 300 W kg⁻¹ in 1 M Na₂SO₄, compared to the chemically activated carbon electrode (E_d of 6.2 Wh kg⁻¹ at P_d of 300 W kg⁻¹). Tobi and Dennis activated physically and chemically a composite of oil palm shell, empty fruit bunch, and oil palm fiber. Electrodes were assembled into coin cells using an H₃PO₄-based gel electrolyte. At a low specific power density of 50 W kg⁻¹, supercapacitors derived from chemically and physically activated composite exhibited specific energy densities of 8.6 Wh·kg⁻¹ and 5.8 Wh kg⁻¹, respectively. At a high specific power density of 500 W kg⁻¹, the specific energy densities of chemically and physically activated carbons reduce to 3.2 Wh kg⁻¹ and 3.4 Wh kg⁻¹, respectively.

Wong et al. [10] used a bimetallic Fe/Co catalyst system to induce graphitization of palm kernel shell-derived carbon for electrodes. CR2032 supercapacitors with these electrodes were assembled using 6 M KOH electrolyte. Although increasing the synthesis temperature (600 °C to 1000 °C) facilitates graphitization, the highest energy density (18.49 Wh kg⁻¹ at 402.15 W kg⁻¹) was obtained for the material synthesized at 600 °C. Paramudita et al. [11] chemically activated oil palm fronds (OPF) using KOH or NaOH at varying temperatures (600 °C, 700 °C, and 800 °C) and produced electrodes with these activated carbons impregnated with H₂SO₄/PVA gel electrolyte. The results demonstrate that the OPF-based supercapacitor activated with KOH at 800 °C exhibits the best performance among the KOH samples, with a specific capacitance of 317.85 F g⁻¹, an energy density of 44.15 Wh kg⁻¹, and a power density of 2150.54 W kg⁻¹. The OPF-based supercapacitor activated with NaOH at 800 °C also exhibits the best performance among the NaOH samples, with the highest specific capacitance of 490.00 F g⁻¹ among others, an energy density of 68.08 Wh·kg⁻¹, and a power density of 2083.33 W kg⁻¹. These results are attributed to the enhanced porosity and surface area of the activated carbons obtained at 800 °C.

In this work, palm kernel shell was chemically activated with KOH and ZnCl₂, and then nitrogen was incorporated into its surface via HNO₃ treatment. Materials, with and without added nitrogen, were used to produce supercapacitor electrodes. The electrodes were impregnated with 1 M H₂SO₄. In addition to evaluating the effect of nitrogen on the electrodes' energy storage capacity, stacks of two and eight CR2032 coin cells were electrically tested to more closely approximate real-world applications.

2. Materials and Methods

2.1. Materials

The African Palm Kern Shell (PKS) was obtained from waste products of African palm oil production in Villavicencio (Meta, Colombia). Potassium hydroxide pellets, solid zinc chloride, polytetrafluoroethylene preparation (60 wt% dispersion in H₂O), and sulfuric acid (97%) were purchased from Merck (Darmstadt, Germany). Acetylene black (AB) was purchased from Protokimica (Medellín, Colombia). Nitrogen grade 4 was used for heat treatment and purchased from Air Products Cryogas (Medellín, Colombia).

2.2. Biomass Characterization

PKS was selected as a precursor for active materials for supercapacitor electrodes. The biomass was ground to a particle size of 1–2 mm using a knife mill. The proximate analysis

and high heating value (HHV) of the raw material were determined in accordance with ASTM International Standards. Klason and acid-soluble lignin were quantified using the Klason method.

2.3. Active Materials

The biomass was impregnated with 6 M KOH and 1 M ZnCl₂ at an activated agent (AA) ratio of 2:1 and 1:1, respectively, for 4 h at room temperature. It was then dried for 12 h at 105 °C. Afterward, the impregnated samples were heat-treated at 700 °C with a heating rate of 5 °C min^{−1} in a nitrogen flow of 100 mL min^{−1} to maximize porosity. The samples were neutralized with 0.1 M HCl for 1 h, washed several times with water to neutral pH, vacuum-filtered, and dried at 105 °C for 12 h, based on our previous work [12]. Activated carbons were superficially modified by impregnation with 30% HNO₃ at a 1:1 impregnation ratio, with constant stirring at 400 rpm for 4 h at room temperature. Finally, the modified activated carbons were dried for 12 h. Figure 1 describes the procedure of activated carbon synthesis (PK700 AND PZ700) and their modification (PK700N and PZ700N).

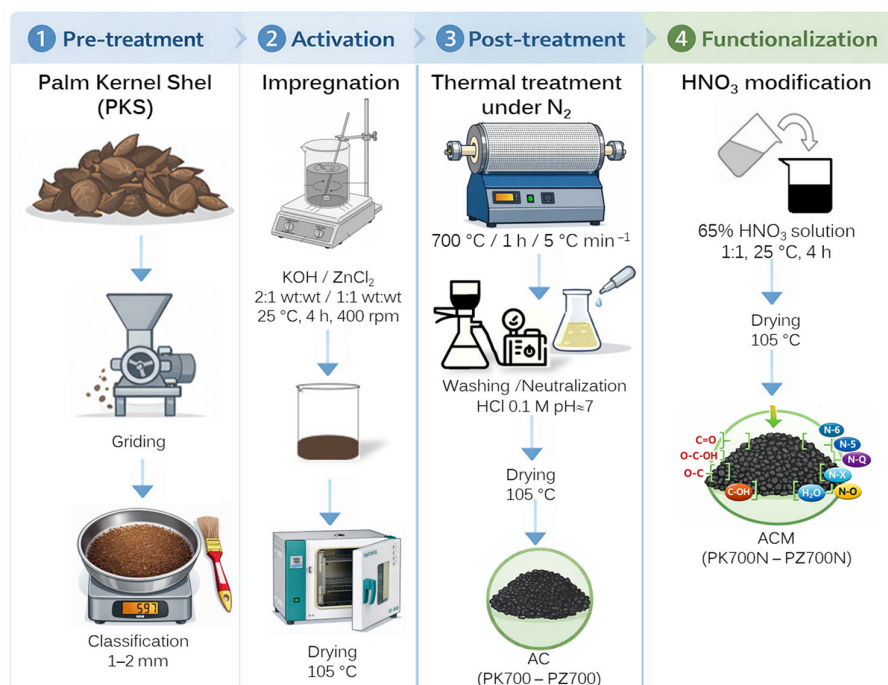


Figure 1. Schematic illustration of activated carbon and the modification process.

2.4. Superficial, Physical, and Chemical Characterization

The elemental composition of the palm kernel shell was determined through ultimate analysis. The surface elemental composition of the activated carbons was characterized using X-ray photoelectron spectroscopy (XPS). XPS measurements were performed using a spectrometer (OMICRON, Klaus, Austria, ESCA+) with MgK α radiation (1253.6 eV), and the spectra were calibrated using the C_{1s} signal at 284.5 eV as a reference (Near Ambient Pressure X-ray Photoelectron Spectroscopy (NAP-XPS); SPECS Surface Nano Analysis GmbH; Berlin, Germany). The morphology of the samples was characterized using scanning electron microscopy (SEM; JEOL JCM-6000plus; JEOL Ltd. Akishima (Tokyo), Japan) at 15 kV with magnifications of $\times 5000$ and energy-dispersive X-ray analysis (EDXA).

N₂ isotherms at -196 °C were measured using an ASAP 2020 Plus (Micromeritics Instrument Corporation Norcross, Norcross, GA, USA). Samples were outgassed overnight at 120 °C under a high vacuum. Specific surface area (S_{BET}) was determined from N₂ isotherms applying the Brunauer–Emmett–Teller model (BET), and the micropore volume

(V) and micropore size (D) were calculated using the Dubinin-Radushkevich (DR) model from N_2 isotherms. The mesopore volume (V_{meso}) was calculated by the difference between the pore volume, $V_{0.98}$, adsorbed at a relative pressure of 0.98, and micropore volume (the Gurvich rule) [13].

2.5. Electrode Preparation, Coin Cell Assembling, and Electrochemical and Electrical Characterization

Electrodes were prepared from a mixture of activated carbon (80 wt%), a conductive agent (Acetylene black) (10 wt%), and polytetrafluoroethylene (PTFE) (10 wt%). A 7 mg portion of the mixture was pasted onto a 12 mm-diameter graphitic disk. The electrodes were immersed in 1 M H_2SO_4 for 5 days and then inserted into an electrochemical cell. The electrodes were introduced into a standard coin cell (CR2030, Xiamen TOB New Energy Technology Co., Ltd.; Xiamen (Fujian), China) without polarity, composed of metallic separators and positive and negative cases, and pressed at 2 USTonb in a manual hydraulic machine. The electrodes were characterized electrochemically in a two-electrode symmetric configuration using a PFA Swagelok-type cell $\frac{1}{2}$ " in a Multipotentiostat Autolab M204 (Metrohm Autolab; Utrecht, The Netherlands). Figure 2 describes the procedure of the two-electrode configuration and the assembly of a CR2032 coin cell.

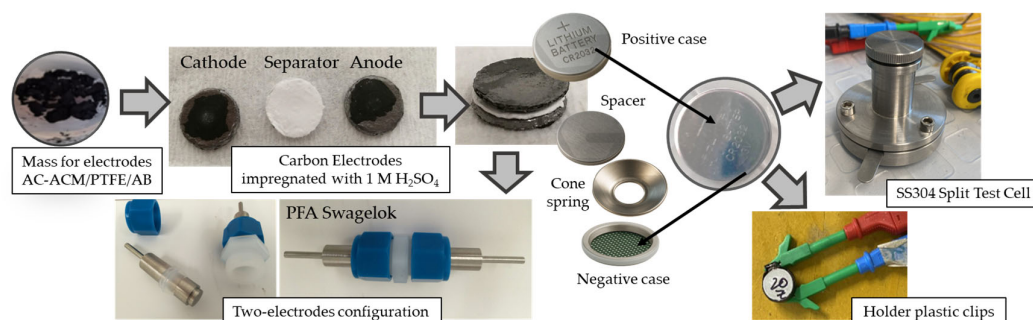


Figure 2. Schematic illustration of a symmetrical supercapacitor for a two-electrode electrochemical cell (Swagelok) and Assembly of a CR2032 coin cell. The arrows collectively represent a step-by-step experimental flow, moving from: Electrodes preparation, followed by electrode fabrication, Coin cell assembly and electrical connection.

Cyclic voltammetry (CV) curves of the electrodes were recorded between 2 mV s^{-1} and 50 mV s^{-1} between 0 V and 0.75 V, and galvanostatic charge–discharge (CP) curves were recorded between 0 V and 0.75 V between 0.125 A g^{-1} and 1 A g^{-1} . The gravimetric capacitance was calculated from the discharge curve between 0 V and 0.75 V according to Equation (1) [14].

$$C_{CP} = \frac{I \Delta t}{2m \Delta V} \quad (1)$$

where I is the discharge current (A), t is the discharge time (s), m the active mass of electrodes, and V is the voltage range (V). The capacitance retention (R_{CP}) was calculated by comparing the gravimetric capacitance, C_{CP} , (F g^{-1}) with the gravimetric capacitance at 0.125 A g^{-1} between 0 V and 0.75 V, Equation (2):

$$R_{CP}(\%) = \frac{C_{CP}}{C_{CP,0.125 \text{ A g}^{-1}}} \times 100 \quad (2)$$

The equivalent series resistance (ESR) of the electrodes, the time charge (τ), and the phase angle were calculated from Electrochemical Impedance Spectroscopy (EIS) over the frequency range of 1 mHz to 100 kHz using a sinusoidal signal of $\pm 10 \text{ mV}$. The maximum

gravimetric capacitance is calculated at the minimum frequency (1 mHz) according to Equation (3) [15]:

$$C_{max} = -\frac{Z''}{m\omega|Z|^2} \quad (3)$$

where Z'' is the imaginary impedance, $|Z|$ the complex impedance, and m is the total weight of the active material (5.6 mg), without binder and conductive additive, for both electrodes.

Interfacial capacitance (IC) in $\mu\text{F cm}^{-2}$ or double-layer capacitance per unit surface area is obtained by dividing the C_{max} per specific surface area (S_{BET}) as in Equation (4):

$$IC = \frac{C_{max}}{S_{\text{BET}}} \quad (4)$$

The coin cell was characterized electrochemically by using a stainless-steel Split Test Cell SS304 (MTI Corporation; Richmond, CA, USA) (Figure S1b). The charge and discharge curves for the coins are recorded at 0.0001 A, 0.001 A, and 0.01 A, with time intervals of 10 s, 20 s, and 30 s, and at two voltage ranges (0.5 V and 0.75 V). The capacitance is measured from the slope of the charge line using the second section of the data to ensure measurement quality and stability. First, the voltage differential between measurements was calculated by subtracting the measurements at each interval and dividing by the time difference (100 ms) at the specific current. The differentials were then averaged to find an average voltage differential. The capacitance, C , of the coins (F) is calculated from the charge curve in the linear region over a differential time interval, using Equation (5) and the average potential (V).

$$C = \frac{i}{\frac{dV}{dt}_{avg}} \quad (5)$$

where i is the charge current (A) and dV/dt_{avg} is the slew rate (V/s) or the rate of change of voltage in Volt per second (V/s).

The cumulative energy of the charge of the cells is calculated from the voltage difference (ΔV) during the charge ($E_{cum,c}$) and discharge ($E_{cum,d}$) as Equations (6) and (7), respectively:

$$E_{cum,c} = \sum I\Delta V\Delta t_{charge} \quad (6)$$

$$E_{cum,d} = \sum I\Delta V\Delta t_{discharge} \quad (7)$$

The cumulative loss of energy in the system during charge ($E_{loss,c}$) and discharge ($E_{discharge}$) are calculated as a function of the initial internal resistance and the discharge current as Equations (8) and (9), respectively:

$$E_{loss,c} = \sum R_{int}I^2\Delta t_{charge} \quad (8)$$

$$E_{loss,d} = \sum R_{int}I^2\Delta t_{discharge} \quad (9)$$

where R_{int} (Ω) is the internal resistance calculated from the voltage difference (ΔV) in volt (V) at the beginning of the discharge (0.50 s), I_c the current in the charge and I_d the current in the discharge in amperes (A) as Equation (10):

$$R_{int} = \frac{\Delta V_{0.5s}}{(I_c + |I_d|)} \quad (10)$$

The efficiency percentage (η_E) and the ideal capacitance (C_{ideal}) in farads (F) of the system are calculated as Equations (11) and (12), respectively:

$$\eta_E(\%) = \frac{E_{cum,d}}{E_{cum,c}} \cdot 100 \quad (11)$$

$$C_{ideal} = \frac{(E_{cum,d} + E_{loss,d})}{\Delta V_d^2} \quad (12)$$

where the voltage difference (ΔV_d) is in volt (V) during discharge.

Approximately 20 cells were assembled and characterized using EIS under the same conditions described above. The average values of capacitance (F), ESR (ohms), system efficiency, and ideal capacitance, along with their confidence intervals, were calculated using Equations (13) and (14).

$$\bar{X} \pm \left(S / \sqrt{n} \right) t_{\alpha/2(n-1)} \quad (13)$$

$$L = \bar{X} \pm \left(S / \sqrt{n} \right) t_{\alpha/2(n-1)} \quad (14)$$

where $\bar{X}$ is the average value, L is the confidence interval, S is the standard deviation, n is the number of data, t is the student and α is the confidence level at 95%.

In this work, we arranged the cells in series as two- and eight-cell connections. Two-coin cells series were connected using a commercial battery holder with plastic clips for CR2032 (Figure S2a), the eight coins series were connected in a non-conductive tube holder, which was homemade with PVC of diameter $\frac{3}{4}$ ", with threaded coupling to which the cables and the LED were adapted (Figure S2b). The eight coins in parallel were supported with plastic clips on a plate (Figure S2c).

The overall capacitance (C_T) in farads (F) and potential difference in the stack (V_T) in volts (V) of several capacitors connected in series is calculated as shown in Equations (15) and (16), respectively [14]:

$$C_T = \left(\frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n} \right)^{-1} = \sum_i^n \frac{1}{C_i}^{-1} \quad (15)$$

$$V_T = V_1 + V_2 + \cdots + V_n = \sum_i^n V_i = nV_i \quad (16)$$

where n is the number of coin cells.

When coin cells are connected in parallel, the total capacitance equals the sum of the individual capacitances (C_n), as expressed in Equation (17). The potential difference for each coin is the same as the potential difference in the stack.

$$C_T = C_1 + C_2 + \cdots + C_n \quad (17)$$

The energy density (E_d) in Wh and power density (P_d) in W of a stacked configuration are expressed as Equations (18) and (19), respectively [14].

$$E_d = \frac{1}{2} C_T V_{stack}^2 = \frac{1}{2} C_T (nV_i)^2 \quad (18)$$

$$P_d = \frac{E_d}{t} \quad (19)$$

The specific energy (Wh kg⁻¹) and specific power (W kg⁻¹) density are calculated by dividing the energy density by the stack's total active mass.

The cycling analysis for two coins in series was conducted at a current density of 0.125 A g^{-1} for 10,000 charge–discharge cycles between 1 V. To assess the response and test the operation of each stack, a simple circuit was set up with a coin cell, a power supply, a switch, and a transistor to allow the energy to flow towards the LED device using a Regulated Power supply (BK Precision 1671A DC).

3. Results

3.1. Physicochemical Characterization of Raw Material

Table 1 shows the proximate analysis, high heating value (HHV), and Klason lignin of the raw material. The proximate analysis and HHV are similar to those reported by other authors from different countries, such as Malaysia [16] and Nigeria [17], as well as regions from Colombia [18]. Furthermore, Klason lignin content is lower than that reported in other works, which ranged from 48% to 53% [19,20].

Table 1. Proximate analysis, HHV, and Klason lignin of palm kernel shell.

Parameter	Valor	Standard
Fixed carbon (% <i>w/w</i>)	19.59	ASTM D3173/D3302M—19 [21,22]
Volatile matter (% <i>w/w</i>)	73.49	ASTM D3175—20 [23]
Ashes (% <i>w/w</i>)	2.03	ASTM D3174—12 (2018) [24]
Moisture (% <i>w/w</i>)	4.89	ASTM D3171/D3173M—17a [25,26]
Sulfur (% <i>w/w</i>)	0.09	ASTM D4239—18 Method A [27]
HHV (kJ kg^{-1})	22,806	ASTM D5865/D5865M—19 [28]
Klason lignin (%)	25.64	ASTM D1106 [29]

3.2. Physicochemical and Superficial Characterization of Activated and Modified Carbons

SEM microphotographs of activated carbons (PK700, PZ700, and HNO_3 modification (PK700N and PZ700N) carbons are shown in Figure 3. The images depict planar structures and variously sized, shaped cracks, similar to those observed by Yacob et al. [30]. KOH liquid was used as an activating agent. Its reaction with the solid at 700°C initiates char formation and releases pores via the formation of potassium species, such as potassium dioxide, potassium carbonate, and hydrogen [31]. Alkali metals intercalated into carbon lattices can act as electron donors, promoting the gasification reaction and creating new pores (Figure 3a) [32]. After surface modification of activated carbon, the surface morphology changes to a porous structure, with some pores blocked by the oxidative effect of HNO_3 (Figure 3b) [33]. Figure 3c shows the PZ700 morphology, which has a more compact structure than PK700, associated with a dehydrating effect, and a mean access pore size of $1.2 \mu\text{m}$. In contrast, PZ700N has a larger mean access pore size of $1.9 \mu\text{m}$ and fewer cavities due to HNO_3 -induced structural destruction (Figure 3d).

Figure 4 shows the nitrogen adsorption–desorption isotherms at 77 K and the pore size distribution (PSD) of activated and modified carbons. The physisorption isotherms for both materials are Type Ib, indicating mainly narrow micropores ($<1 \text{ nm}$) with a hysteresis cycle [13]. According to the PSD, PK700 and PZ700 exhibit primary peaks at 0.59 nm and 0.5 nm , respectively. The modified samples show a marked decrease in small-diameter pores, with a higher presence of pores near 1.0 nm and 1.2 nm for PK700N and PZ700N, respectively. Table 2 compiles the porosity and superficial properties of activated and HNO_3 -modified carbons.

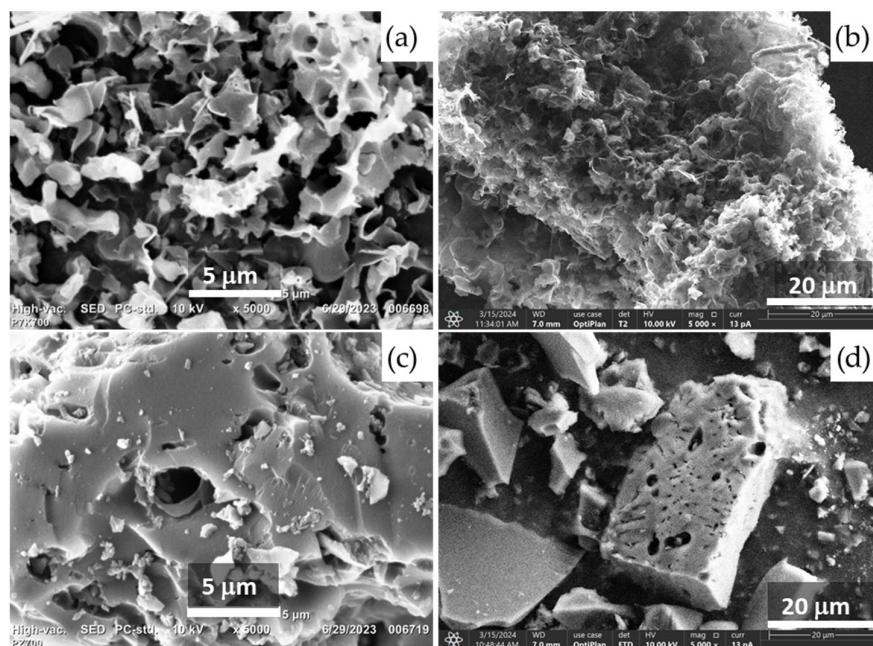


Figure 3. SEM microphotography at $\times 5000$ and 10 kV: (a) PK700; (b) PK700N; (c) PZ700 and (d) PK700N.

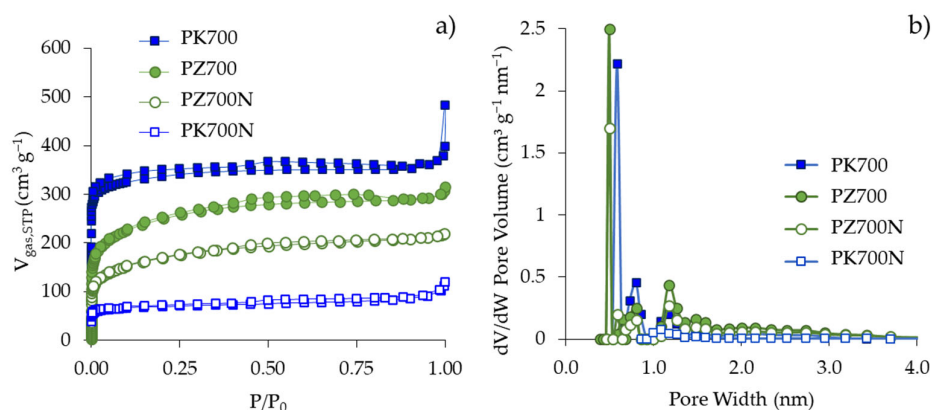


Figure 4. (a) N_2 adsorption–desorption isotherms at 77 K; (b) Pore size distribution by DFT of activated and modified carbons.

Table 2. Porosity, superficial properties, and elemental composition of activated carbons.

Sample	S_{BET} $m^2 g^{-1}$	V $cm^3 g^{-1}$	D nm	$V_{0.98}$ $cm^3 g^{-1}$	V_{meso} $cm^3 g^{-1}$	C_{1s} wt%	O_{1s} wt%	N_{1s} wt%
PK700	1181	0.542	0.77	0.566	0.024	85.53	13.61	0.86
PK700N	264	0.093	0.79	0.146	0.053	77.78	20.84	1.38
PZ700	877	0.296	1.23	0.426	0.130	89.34	9.69	0.97
PZ700N	589	0.196	1.19	0.306	0.110	83.39	14.52	2.09

The high-resolution XPS C_{1s} spectrum for all Figure S2 was resolved into six peaks related at ~ 284.5 eV (C=C), ~ 285.4 eV (C–C), ~ 286.3 eV (C–OH), ~ 287.3 eV (C=O), ~ 288.6 eV (O=C–OH), and ~ 290.2 eV (π – π^* in aromatic rings) [34]. The high-resolution XPS O_{1s} spectrum was resolved into five peaks ~ 530.2 eV (C=O), ~ 531.2 eV (O=C–OH, C=O, O=C), ~ 532.3 eV (O–C, COH), ~ 533.5 eV (COOH), and ~ 534.8 eV (Oxygen and H_2O chemisorbed) [35]. The high-resolution XPS N_{1s} spectrum of the samples was deconvoluted into four peaks at binding energies of ~ 398.8 eV (N-6), ~ 399.8 eV (N-5), ~ 401.2 eV

(N-Q), and ~ 402.3 eV (N-X). The modified sample shows an additional peak at ~ 405.6 eV (N-O), indicating oxidized nitrogen species [36]. Furthermore, the HNO_3 -modified samples showed an increase in oxygen- and nitrogen-containing functional groups, reaching 2.09 wt% in PZ700N, which is higher than in PK700N. Table 2 presents the elemental superficial composition of activated carbons. The high-resolution spectra of $\text{C}_{1\text{S}}$, $\text{O}_{1\text{S}}$, and $\text{N}_{1\text{S}}$ are shown in Figures S3 and S4, and the binding energies corresponding to the functional groups are listed in Table S1.

3.3. Electrochemical and Electrical Performance

3.3.1. Two-Electrode Electrochemical Performance

Figure 5 depicts the cyclic voltammetry and galvanostatic charge–discharge curves, CVCs and GCDs, respectively, for samples PK700 and PK700N, as a representation, in the two-electrode configuration with H_2SO_4 . The CVCs were quasi-rectangular, and the GCDs were triangular, in both samples, without oxide-reaction peaks. Also, the symmetrical shape was preserved even at higher scan rates and load current densities (I_d). Figure 6a,b shows a progressive decrease in the gravimetric capacitance and capacitance retention at different current densities (I_c), respectively. Specifically, C_{CP} ranges from 21 F g^{-1} to 40 F g^{-1} for PK700 and from 17 F g^{-1} to 36.5 F g^{-1} for PK700N and PZ700N, whereas PZ700 exhibits the lowest gravimetric capacitances (3 F g^{-1} to 23 F g^{-1}). When comparing capacitance retention across load current densities, PK700, PK700N, and PZ700N show similar behaviors, retaining up to 50% at 2 A g^{-1} , whereas PZ700 consistently performs worse, retaining the least capacitance and corresponding to the lowest nitrogen functional group content.

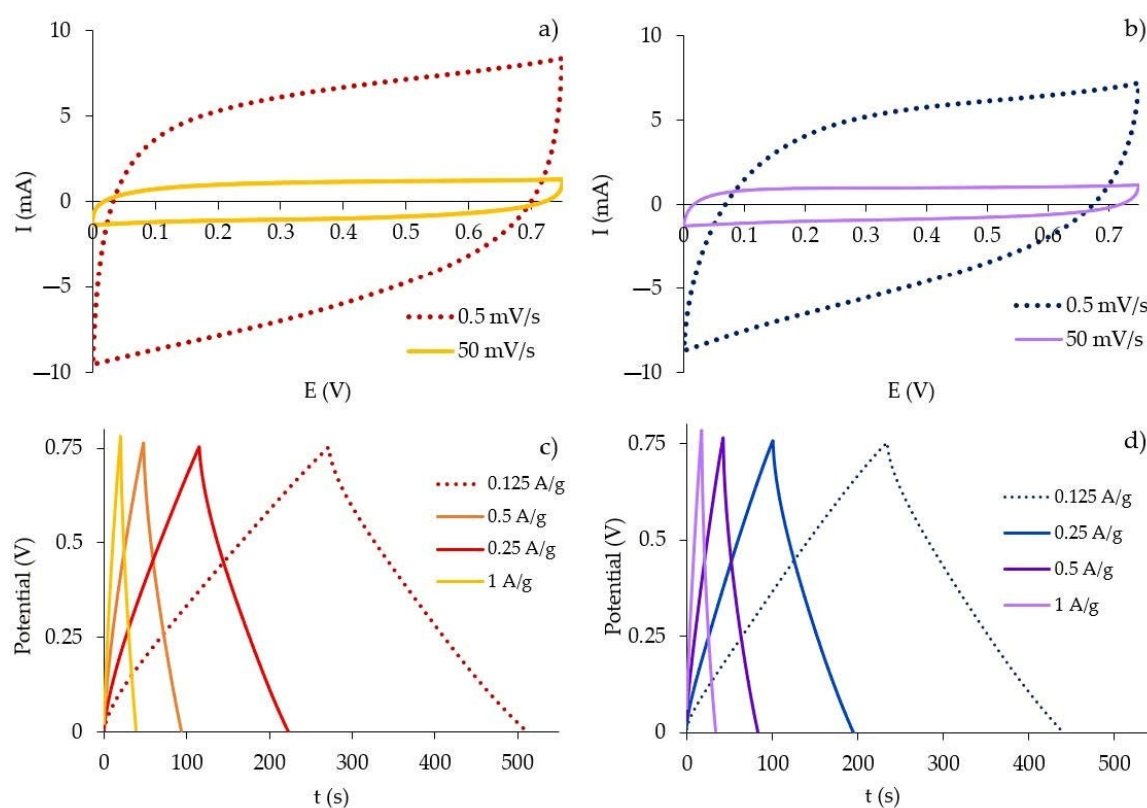


Figure 5. Cyclic voltammetry curves: (a) PK700; (b) PK700N. Galvanostatic charge–discharge curves: (c) PK700; (d) PK700N.

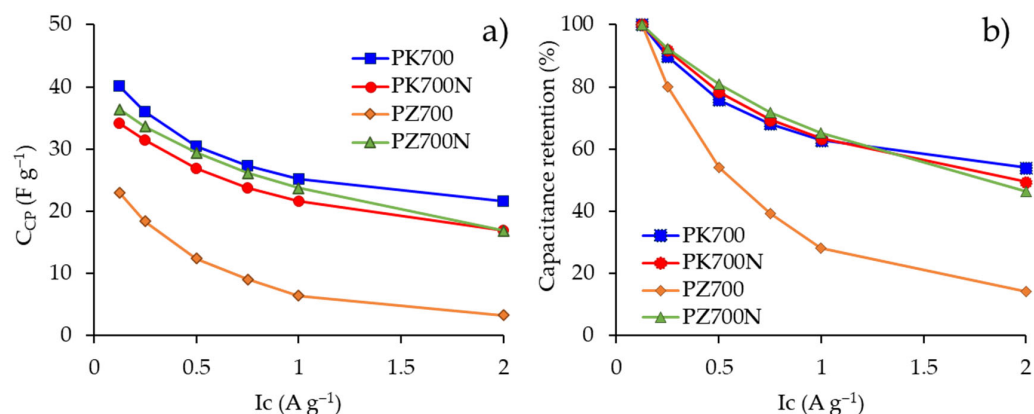


Figure 6. (a) Gravimetric capacitance at different current load densities; (b) Capacitance retention at different current load densities for activated carbons and modified.

Figure 7 shows the Nyquist diagrams from Electrochemical Impedance Spectroscopy (EIS) for activated carbons and their modifications. The curves for all samples are similar to those of typical porous carbon electrochemical capacitors. In the high-frequency region, all samples exhibit a well-defined semicircle, indicative of charge-transfer resistance at the electrode-electrolyte interface. However, PZ700 and PZ700N display a wider semicircle than the other samples, indicating higher transfer and mass-transport limitations. The median frequency region marks the transition between surface phenomena and diffusion (the Warburg region). Here, PK700 and PZ700 display nearly vertical lines, indicating more efficient ion diffusion into pores than PK700N and PZ700N. At the lowest frequency, PK700 has the highest maximum gravimetric capacitance (C_{max}) among the samples.

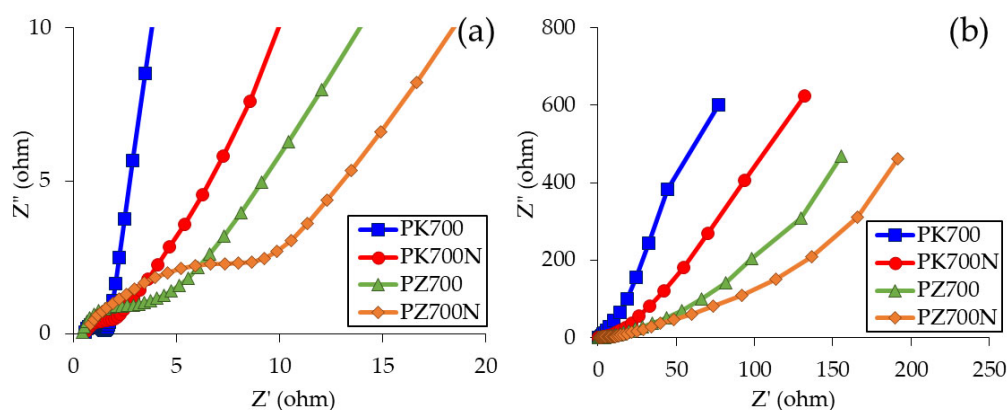


Figure 7. Nyquist diagrams for activated carbons and modified carbons. (a) amplified range; (b) complete range.

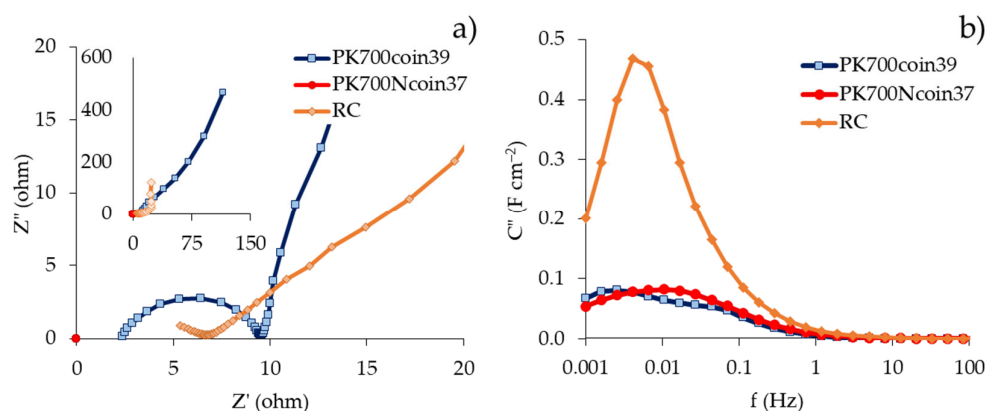
Table 3 summarizes the electrochemical properties from EIS in a two-cell configuration, revealing that C_{max} is similar for all except PZ700. PZ700N exhibits the highest ESR value, attributed mainly to its high surface nitrogen content, which enhances pseudo-capacitance. The interfacial capacitance (IC) was calculated from the average C_{max} and ranged from ~ 10 to $\sim 25 \mu F cm^{-2}$, values typical of carbonaceous electrodes. PK700N has the highest IC value, which may be due to oxygen- and nitrogen-containing functional groups that introduce pseudocapacitive effects, as well as the porous diameter. Table S2 presents gravimetric capacitance and ESR values from EIS for all activated carbon and modified electrodes.

Table 3. Average electrochemical properties by EIS of activated carbon electrodes in a two-electrode configuration with their standard deviation (S) and confidence interval at 95%.

Sample	C_{max} (F g ⁻¹)	S (F g ⁻¹)	ESR (Ω)	S (Ω)	IC (μ F cm ⁻²)
PK700	56.2 $\pm$ 9.2	11.9	2.1 $\pm$ 0.3	0.4	4.8
PK700N	52.8 $\pm$ 5.4	6.4	4.6 $\pm$ 2.2	2.9	20.0
PZ700	36.3 $\pm$ 6.0	6.5	7.1 $\pm$ 3.3	3.6	4.1
PZ700N	50.0 $\pm$ 12.4	10.0	11.9 $\pm$ 15.2	12.3	8.5

3.3.2. Coin Cell Electrochemical Performance

Figure 8a shows the Nyquist diagram from EIS for a representative coin with activated carbon (PK700coin39) and modified activated carbon (PK700Ncoin37) electrodes and a commercial coin as a reference. The main challenge during electrochemical characterization was ensuring consistent performance across each assembly. Approximately fifty (50) cells were configured; however, some were dismissed due to high resistance, contact issues, or high cycles of use. Tables S3 and S4 present the gravimetric capacitance, ESR, the real part of the capacitance (C'), and the losses of the capacitance (C'') from EIS measurements of individual coin cells. The electrochemical performance of the coin cells CR2032 was similar to that observed in Figure 8a. high frequencies, a semicircle is observed, followed by a gradual change in slope that represents Warburg diffusion and reflects the diffusive effects of the chemical species along the electrode. In the low-frequency region (<1 Hz), it shows a vertical line, indicating capacitive behavior. Figure 8b shows the evolution of the loss of the capacitance (C'') vs. frequency. The maximum at a frequency f_0 represents a dielectric relaxation time (τ), the time it takes to store the maximum energy.

**Figure 8.** (a) Nyquist diagram; (b) Gravimetric capacitance at different current load densities for coin cells.

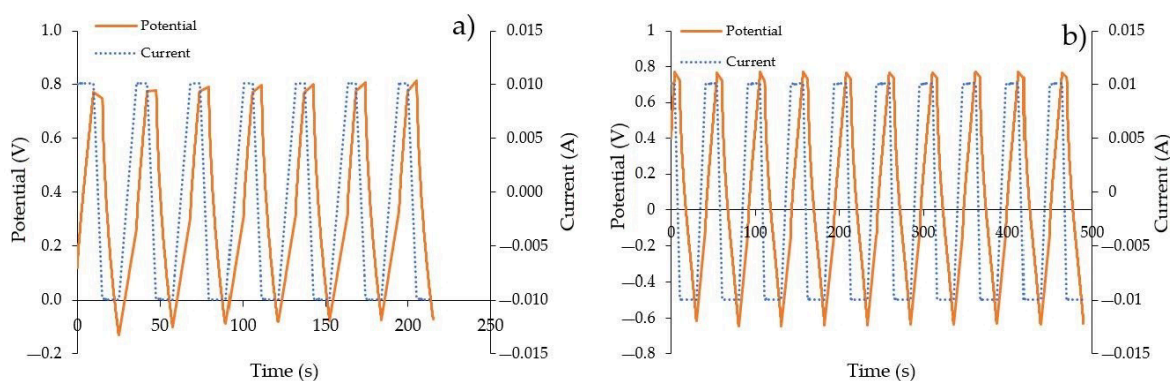
These curves were compared with a commercial coin (PowerStor 1.5 F—5.5 V). Table 4 shows the average values of gravimetric capacitances, ESR, the real part of the capacitance C' (F), and losses of capacitance that occur during charge storage C'' (F) for coin cells. The average gravimetric capacitance of the activated carbon electrodes, compared with that of the modified activated carbon electrodes in the Swagelok cell, showed a similar trend to that in the coin cell. However, ESR values for coin cells were higher than for Swagelok cells due to the resistance in the joints between the materials. Moreover, this resistance is a combination of the material's electrical resistance and parasitic resistance. Parasitic resistance may result from overall mechanisms, materials, or impurities at the contact surfaces.

Table 4. Average electrochemical properties from EIS for coin cells with their standard deviation (S) and confidence interval at 95%.

Sample	C_{EIS} (F g ⁻¹)	S_C (F g ⁻¹)	ESR (Ω)	S_{ESR} (Ω)
PK700coin	56.6 ± 17.7	35.5	17.9 ± 3.1	6.3
PK700Ncoin	56.9 ± 5.8	6.9	14.9 ± 4.1	5.0
PZ700coin	33.0 ± 5.7	3.6	18.6 ± 13.4	8.4
PZ700Ncoin	47.4 ± 9.5	5.9	23.1 ± 20.5	12.9

3.3.3. Electrical Performance of Series and Parallel Arrangements

Electrical performance was evaluated for coins with samples PK700 and PK700N, which showed better electrochemical performance than samples PZ700 and PZ700N. Figure 9 shows the charge/discharge cycle curves at different times, 0.75 V at 10 s and 20 s, for a one-coin cell (PK700coin28) as an example, and Figure S5 depicts the charge/discharge curves at 0.5 V at 10 s and 20 s for a one-coin cell (PK700coin30). Table S5 shows the electrical evaluation of individual coin cells at different currents (0.0001 A, 0.001 A, and 0.01 A), 20 s of changing the time, and different voltage limits (0.5 V and 0.75 V). The coin cells achieved their best performance at 1 mA at 0.75 V, with charge and discharge times of 20 s. Table 5 shows the average electrical properties of individual coin cells at different voltage potentials and currents.

**Figure 9.** Charge/discharge curves for one coin cell (PK700coin28): at (a) 10 s; (b) 20 s at 0.75 V and 0.01 A.**Table 5.** Average of electrical properties and their confidence interval of individual coin cells at 20 s.

Sample	EV (V)	I (A)	R_{int} (Ω)	η_E (%)	C_u (F)	C_i (F)	E_{exp} (Wh kg ⁻¹)	P_{exp} (W kg ⁻¹)
PK700	0.5	0.0001	31.2 ± 14.8	74 ± 7	0.27 ± 0.05	0.27 ± 0.04	1.7 ± 0.3	302 ± 48
		0.001	27.0 ± 15.2	53 ± 7	0.18 ± 0.02	0.24 ± 0.02	1.1 ± 0.5	202 ± 27
		0.01	19.7 ± 8.8	21 ± 12	0.13 ± 0.03	0.19 ± 0.03	0.8 ± 0.4	142 ± 28
	0.75	0.0001	28.6 ± 9.7	75 ± 6	0.28 ± 0.04	0.43 ± 0.04	3.9 ± 1.9	701 ± 106
		0.001	24.1 ± 9.3	52 ± 7	0.18 ± 0.02	0.25 ± 0.02	2.5 ± 1.2	447 ± 58
		0.01	24.8 ± 11.0	31 ± 11	0.15 ± 0.02	0.21 ± 0.02	2.0 ± 1.0	364 ± 56
PK700N	0.5	0.0001	13 ± 7.5	82 ± 30	0.25 ± 0.08	0.28 ± 0.17	1.5 ± 0.5	277 ± 85
		0.001	11 ± 9.7	60 ± 42	0.16 ± 0.09	0.16 ± 0.13	1.0 ± 0.5	177 ± 98
		0.01	7 ± 5.9	8 ± 12	0.07 ± 0.11	0.03 ± 0.04	0.4 ± 0.7	78 ± 119
	0.75	0.0001	12 ± 12.4	86 ± 37	0.24 ± 0.06	0.28 ± 0.20	3.4 ± 0.9	609 ± 154
		0.001	10 ± 11.3	62 ± 39	0.16 ± 0.06	0.14 ± 0.11	2.2 ± 0.9	392 ± 160
		0.01	11 ± 8.1	28 ± 17	0.12 ± 0.12	0.06 ± 0.08	1.7 ± 1.7	312 ± 303

Different arrangements of supercapacitors in series and parallel with the coin cells, with the most stable behavior, were evaluated across different voltage and current ranges. Two assemblies in series, two- (Figure 10a) and eight-coin cells (Figure 10b), and one in parallel with eight coins (Figure 10c) were conducted. The capacitances of the series and parallel assemblies were compared with their theoretical values, calculated for each unit using Equations (15) and (17), respectively. The stacks were constructed using cells that performed best in the individual assays. The individual capacitances of the coin cells used in series and parallel stacks are shown in Table S5.

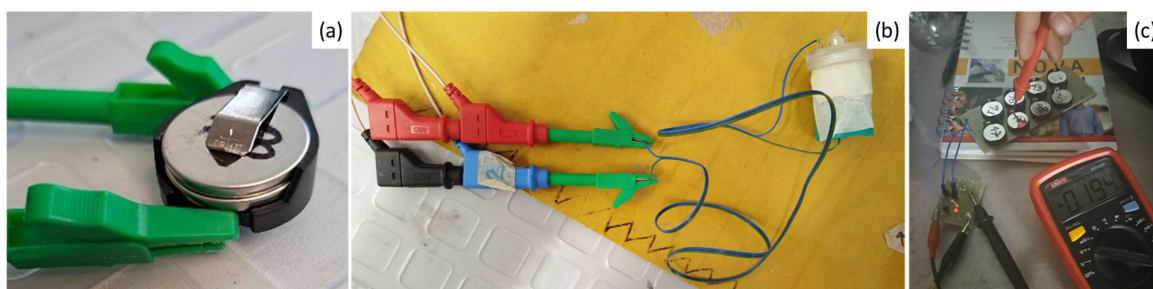


Figure 10. Assembly of (a) two-coin cells in series, (b) eight-coin cells in series, and (c) eight-coin cells in parallel.

In a series arrangement, the capacitance of the stack is lower than the capacitance of each coin. The capacitance values for a stack of two coins (27–28 and 29–30) are presented in Table 6. The differences between assays correspond to each cell’s conformation.

Table 6. Electrical properties of a two-coin cell stack in series at 20 s.

27–28														
V (V)	I (A)	C ₂₇ (F)	$\eta_{E,27}$ (%)	C ₂₈ (F)	$\eta_{E,28}$ (%)	C _{2S,teo} (F)	R _{int,o} (Ω)	$\eta_{E,2Sexp}$ (%)	C _{2S,exp} (F)	C _i (F)	V _{2S} (V)	Error _{C2S} (%)	E _{2S,exp} (Wh kg ^{−1})	P _{2S,exp} (W kg ^{−1})
0.5	0.0001	0.37	42.0	0.20	63.7	0.129	9.1	78.0	0.169	0.63	1.0	23.8	2.1	378
	0.001	0.23	53.4	0.13	36.0	0.082	10.0	43.8	0.112	0.06	1.0	26.6	1.4	249
	0.01	0.10	6.1	0.11	2.2	0.053	9.4	1.5	0.071	0.01	1.0	24.9	0.9	159
0.75	0.0001	0.22	44.1	0.23	63.4	0.112	9.4	77.0	0.186	0.55	1.5	39.7	5.2	933
	0.001	0.14	52.1	0.14	26.3	0.070	7.4	40.7	0.115	0.06	1.5	38.9	3.2	579
	0.01	0.13	36.5	0.14	15.7	0.066	9.3	0.3	0.087	0.01	1.5	24.1	2.4	435
29–30														
0.5	0.0001	0.187	58.3	0.208	70.6	0.098	13.2	69.9	0.118	0.487	1.0	16.9	1.5	264
	0.001	0.132	43.2	0.108	44.2	0.059	12.7	38.1	0.069	0.033	1.0	13.8	0.9	154
	0.01	0.106	1.4	0.077	0.4	0.045	12.9	5.4	0.042	0.042	1.0	6.1	0.5	94
0.75	0.0001	0.205	61.7	0.188	76.3	0.098	12.2	72.4	0.112	0.080	1.5	12.4	3.1	563
	0.001	0.145	41.8	0.114	59.2	0.064	10.9	18.9	0.067	0.038	1.5	4.4	1.9	335
	0.01	0.104	0.5	0.088	27.1	0.048	13.4	1.3	0.051	0.019	1.5	7.4	1.4	258

The capacitance errors were high (>10%), the pair 29–30 showed better behavior than 27–28, which depended on the individual performance. The specific energy density ranged from 1.6 Wh kg^{−1} to 3.1 Wh kg^{−1} and was calculated using Equation (18). Figure 11 shows the cyclability analysis for a two-coin cell stack in series (coins 25–26). The charge/discharge curves of the first and last cycles showed a quasi-triangular shape, but the arrangement exhibited high resistance (Figure 11b). The gravimetric capacitance was calculated from the discharge curve. The capacitance retention after 2100 cycles was 57%, showing good stability after 900 cycles (Figure 11c).

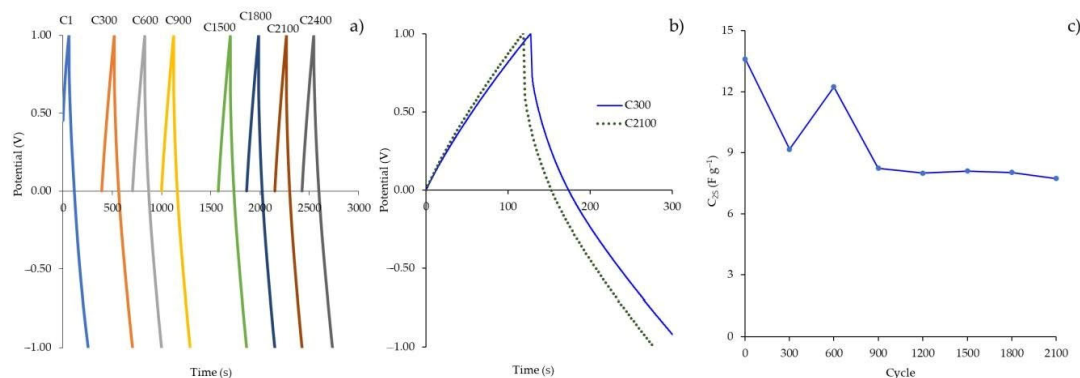


Figure 11. Cyclability analyses for a two-coin cell stack in a series arrangement: (a) charge/discharge curves; (b) Charge/discharge curves of cycles 300 and 2100; (c) Gravimetric capacitance vs. cycle.

To increase the stack's energy storage capacity, eight-coin cells were connected in parallel. Table 7 shows the capacitance values of the eight-coin cell arrangement in series (coins: 17, 21, 23, 24, 25, 26, 29, and 30) and eight-coin cell arrangement in parallel (coins: 40, 41, 43, 44, 46, 47, 48, and 49) and Table S5 shows the electrical properties of the individual coins of the both arrangements. The design of coin cells requires thin electrodes with low active material mass; hence, alternative designs are preferable for bulkier supercapacitors.

Table 7. Electrical properties of eight-coin cells stack in series and parallel at 20 s.

Coin	$EV_{20\text{ s}}$ (V)	I (A)	$R_{int,o}$ (Ω)	η_E (%)	C_{teo} (F)	C_{exp} (F)	C_i (F)	error %	ΔV (V)	E_{exp} (Wh kg ⁻¹)	P_{exp} (W kg ⁻¹)
8S	0.5	0.0001	169.4	74.4	0.026	0.026	0.029	1.4	4.0	1.3	233
	0.5	0.001	152.0	57.3	0.018	0.019	0.019	5.1	4.0	0.9	168
	0.5	0.01	394.8	0.1	0.01	0.012	0.015	18.3	4.0	0.6	107
	0.75	0.0001	876.2	79.4	0.026	0.029	0.064	8.5	6.0	3.2	576
	0.75	0.001	819.0	47.5	0.018	0.016	0.044	10.7	6.0	1.8	319
	0.75	0.01	605.7	34.9	0.013	0.014	0.022	7.5	6.0	1.6	284
8P	0.75	0.001	11.3	66.4	1.66	1.514	3.194	9.6	0.75	2.6	475
	0.75	0.01	6.6	73.6	1.38	1.364	3.205	1.4	0.75	2.4	428

EV: Potential; I: Current; t: Time; 8S: 8 coin-cell in series, 8P: 8 coin-cell in parallel; exp: Experimental.

It should be emphasized that the superior performance observed for the parallel configuration is a system-level, operating-point-dependent effect rather than an intrinsic improvement in the individual coin cells. In this work, electrochemical impedance spectroscopy (EIS) was used to determine the intrinsic ESR at the coin-cell level. At the same time, the effective internal resistances of the series and parallel stacks were inferred from the initial voltage drop during galvanostatic discharge. Under the specific load conditions analyzed, the parallel arrangement results in a lower equivalent resistance and improved impedance matching with the external load, consistent with the physical principles governing power transfer. However, the condition of maximum power transfer is not necessarily achieved.

To test the supercapacitor's charge capacity, a circuit was assembled to light an LED bulb (Figure 12a) and to determine whether it stores enough charge to activate the transistor that provides the path for current to turn on the LED (Figure 12b). These curves are similar to a typical RC circuit. The supercapacitor C1 is powered by a source V1. When switch S1 is closed, the device begins charging, and when switch S2 is closed, current flows through transistor Q1, turning on the LED powered by V2. The transistor turns the LED on until the current passing through the diode is very low. The minimum voltage to light an LED bulb is 1 V. If the supercapacitor voltage is below 1 V, the LED bulb will not light, because the maximum voltage from the developed supercapacitors is 0.75 V. In a series arrangement,

the voltage can increase (e.g., two 1.5 V coin cells), but an additional circuit to turn the LED on would be necessary. A transistor is used as a digital switch to control the passage of current. Therefore, to turn on the LED, an external 5 V power source and a resistor are required to protect the circuit from damage.

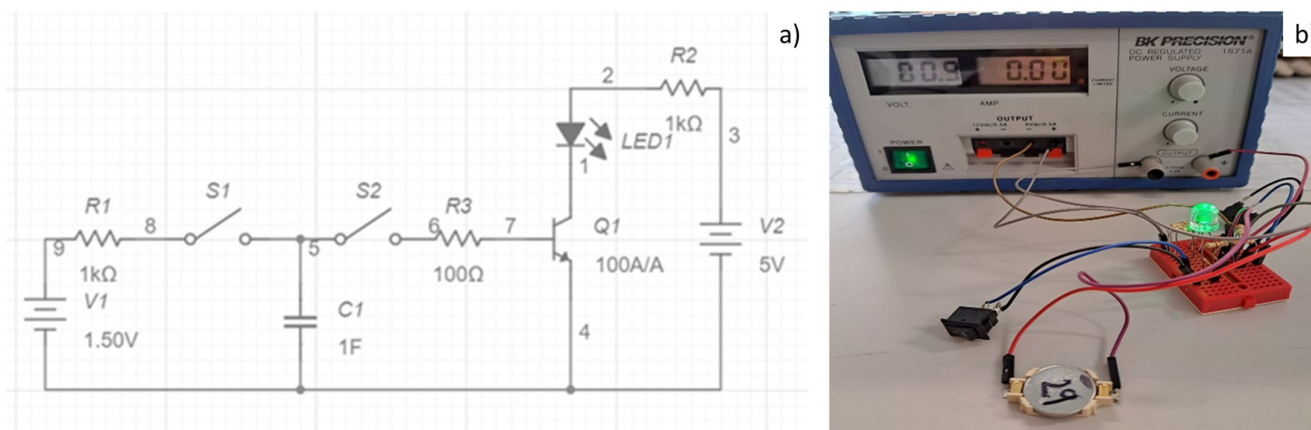


Figure 12. (a) Electrical circuit and its (b) setup to light an LED with a one-coin cell (P7K700coin29). The two small arrows pointing outward from the LED indicate light emission.

4. Discussion

4.1. PKS Activated and Modified Carbons for Two-Electrode Configuration

The activated carbon from PKS (PK700) exhibited a high specific surface area of $1181 \text{ m}^2 \text{ g}^{-1}$, a key factor in enhancing its electrochemical performance in energy storage devices by amplifying electrostatic effects in EDLCs. However, after HNO_3 modification, the specific surface area of PK700N decreased noticeably ($264 \text{ m}^2 \text{ g}^{-1}$) and, probably due to the insertion of functional groups into the porosity, mainly N–O and carbonyl groups, that could improve the wettability of the surface and pseudo-faradic reactions that enhance the ion transport and could increase the overall energy charge storage [37,38].

The CVCs have a quasi-rectangular shape, while the GDCs are triangular, indicating that both samples behave as ideal EDL capacitors. The gravimetric capacitance at 0.125 A g^{-1} for PK700 and PK700N was 40 F g^{-1} and 34 F g^{-1} , respectively. The decrease in the gravimetric capacitance after modification may be due to the blockage of micropores by oxygen and nitrogen functional groups, thereby reducing their volume [33]. This suggests that energy storage is largely determined by specific surface area rather than pseudocapacitive effects. However, capacitance retention across different load current densities is similar for both samples, and at 1 A g^{-1} , it is approximately 63%. The ESR of PK700N is higher than that of the sample PK700, which is consistent with the increase in the percentage of nitrogen on the surface of the sample PK700N. Furthermore, the average micropore size for both samples is $\sim 0.78 \text{ nm}$, which is equivalent to the optimal size for hydrated molecules of SO_4^{2-} [39]. This behavior could be attributed to the higher nitrogen content, which improved surface wettability and electron transfer [12].

The presence of open cavities in PK700 improves the electrolyte's accessibility relative to PZ700. This accessibility facilitates the adsorption of the liquid electrolyte at the surface. It enables interaction between electrons from the activated carbon and ions from the electrolyte [7], thereby improving the electrochemical performance of PK700 and making it more suitable for electrode development. The surface chemistry of the activated carbons was investigated using XPS to assess the effects of the activating agent and nitric acid oxidation on heteroatom incorporation. KOH activation promotes a higher oxygen content than ZnCl_2 activation (O/ C_{XPS} ratios were 0.159 for PK700 and 0.108 for PZ700), while the

N/C_{XPS} ratio was 0.01 in both cases. After functionalization, the O/C_{XPS} ratios were 0.268 for PK700N and 0.174 for PZ700N, confirming the effective introduction of oxygenated and nitrogenated functionalities that enhance surface polarity, improve electrolyte wettability, and generate redox-active sites. This functionality is associated with the presence of carboxylic and carbonyl surface groups, as well as N-O and N-5 nitrogen surface groups. However, the functionalization process reduced the specific surface area, particularly for PK700 (1181 m² g^{−1} to 264 m² g^{−1}), indicating pore blockage and partial structural degradation. In contrast, ZnCl₂-derived carbon better preserved its porosity (from 877 to 589 m² g^{−1}) while achieving the highest nitrogen enrichment, suggesting greater structural stability under oxidative conditions.

Among the evaluated materials, PZ700N shows the best balance between porosity and heteroatom doping, both of which are linked to improved charge transfer and electrochemical performance. The oxidized nitrogen species (N-O) at ~405.6 eV increased significantly in PZ700N (59.8%) compared with PK700N (25.2%), thereby raising the gravimetric capacitance, as reported in our previous work [38]. PK700 has the highest specific surface area and contains more oxygen-containing functional groups at ~533.5 eV, carboxyl groups. These functionalities are especially significant in aqueous electrolytes because they improve wettability by increasing surface polarity, facilitating electrolyte penetration, reducing interfacial resistance, and enhancing electrochemical performance [40,41]. The oxygen and nitrogen functional group contents of all samples are shown in Table S1.

These results highlight an important trade-off between surface functionalization and textural properties, emphasizing the need for controlled oxidation to optimize carbon materials for high-performance energy storage. Although the operating voltage window and the electrode material establish the maximum energy density in EDLC devices, the actual energy density largely depends on the specific capacitance achieved. This capacitance is strongly influenced by electrode structures such as accessible specific surface area, pore size distribution, and pore connectivity, as well as by surface chemistry, including oxygen- and nitrogen-containing functional groups. Therefore, activation and surface modification can improve intrinsic energy density by facilitating ion transport, enhancing wettability, and increasing charge storage efficiency, even when the voltage window remains unchanged.

4.2. Coin Cells with PKS-Activated Electrodes in Series and Parallel Arrangements

The maximum specific capacitance at the lowest frequency was slightly higher for the activated carbon (56.2 F g^{−1}) than for its modified form (56.9 F g^{−1}). Both samples showed a well-defined semicircle, indicating good charge transfer and fast charge/discharge. However, the line in the low-frequency region for both samples is not perpendicular to the *x*-axis, which is typical of activated carbon as an active material and indicates the difficult accessibility of hydrated ions in certain pores [42]. Figure 13 shows the electrical equivalent circuit of a supercapacitor, consisting of an internal resistor (*R*_{int}) and a capacitor in series.

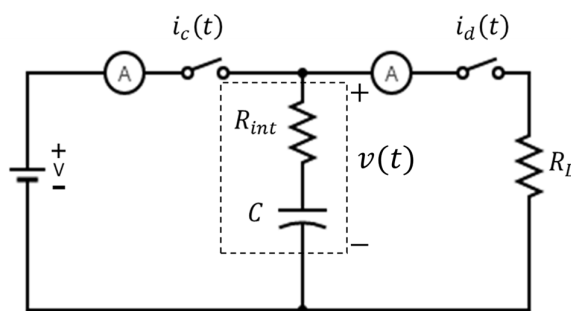


Figure 13. Electrical equivalent circuit represents a supercapacitor.

At $t = 0$, switch S1 (right side) is closed, initiating the charging process of the coin cell or the supercapacitor coin stack. The charging process continues until time $T = T_c$, at which point the device is considered fully charged. At this instant, switch S1 opens and switch S2 closes, initiating the capacitor's discharge. During both stages, the device voltage $v(t)$, the charging current $i_c(t)$, and the discharging current $i_d(t)$ are recorded. The instantaneous charging and discharging powers are obtained by multiplying voltage and current and integrating over time, which allows estimation of the energy involved in the charge and discharge processes, respectively. The difference between the energy supplied during charging and the energy recovered during discharge is due to total energy losses in the system, which include both charging and discharging losses. The device's equivalent internal resistance is estimated via a numerical fitting procedure using a solver, which enforces the circuit dynamic equation during charge and discharge transients and supports the calculation of efficiency and ideal capacitance, as described in Equations (11) and (12).

The capacitance of each coin was determined by using the galvanometric method at a constant current of less than 1 mA to avoid parasitic resistance in the assembly, based on the total active weight of the stack, which corresponds to the mass of the electrode without the case, binder, or other cell parts. The individual coin cell showed an energy density of 0.8–3.9 Wh kg^{−1} and a power density of 142–447 W kg^{−1}. PK700 showed the highest values at the lowest current (0.0001 A) and 0.75 V, and, in most cases, showed the highest internal resistance.

Stacking supercapacitors allows multiple cells to operate together, exceeding the limits of a single cell. This configuration will be heavier and suitable for applications where weight and volume are not critical. When cells are connected in series, the stack can provide an operating voltage higher than that of a single cell, and the potential difference across each cell should not exceed the electrolyte's decomposition potential. Also, if one or more capacitors in a series bank have different ratings, there is a risk of overcharging or overdischarging during charging or discharging, which could result in electrolyte decomposition [43]. The energy density values were comparable to those of EDCL devices with bio-electrodes [44,45]. As the number of cells in a series increases, the total capacitance decreases, while the voltage and energy density increases. Analysis of series-connected two- and eight-coin-type supercapacitors, although the arrays used different coin types, shows that specific energy density values are similar to those of individual coins (1.8–2.4 Wh kg^{−1}). Series connections increase the overall operating voltage but do not proportionally improve the specific energy or power per unit of total array mass.

The capacitance values in the parallel arrangement were significantly higher than in the series arrangement; however, the experimental errors were around 10%. Also, the specific energy density values in a parallel arrangement were around 2.6 Wh kg^{−1} and 521 Wh kg^{−1} at 0.001 A and 0.75 V, higher than in a series arrangement at the same conditions (1.8 Wh kg^{−1} and 353 Wh kg^{−1}). Connecting the cells in series increased the operating voltage to 6 V by integrating eight cells, but this reduced the effective capacitance and specific energy density. This effect is associated with the sum of the internal resistances and the potential distribution between the electrodes. Despite experimental errors of approximately 10%, the observed trends are consistent and demonstrate the inherent trade-off between maximizing energy output and extending the voltage range. Figure 14 shows the Ragone plot of the experimental points for the different arrangements evaluated.

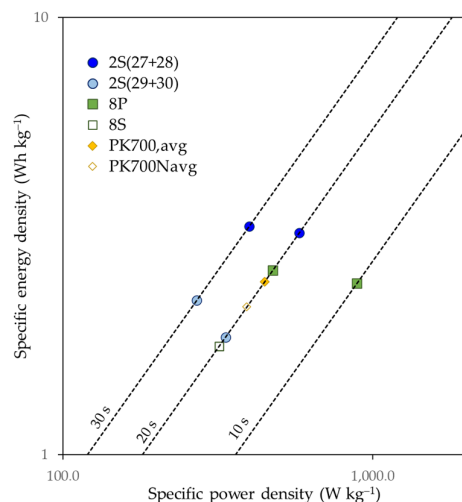


Figure 14. Ragone plot of experimental points of supercapacitors with carbon electrodes at 0.001 A and 0.75 V.

5. Conclusions

Supercapacitors are strategic devices for modern energy systems, combining high power, long lifespan, and efficient operation to complement batteries in applications where speed and durability are significant. However, commercial supercapacitors typically offer high performance, but detailed information about the materials used in their electrodes is often unavailable. In this context, using materials derived from local waste for electrode manufacturing is emerging as an effective strategy to significantly reduce the carbon footprint of these devices. Furthermore, by using electrodes derived from biomass or agro-industrial waste, supercapacitors enable the reuse of materials that would otherwise become waste, thereby directly supporting circular economy and energy transition strategies. Coin-type supercapacitors are being developed using activated carbon electrodes from African palm kernel residues chemically activated with KOH. These materials are promising due to their ease of processing, high specific surface area, and chemical stability. These features do not modify the intrinsic energy density of the devices, which is determined by the electrode materials and the operating voltage window. Instead, improved performance was observed in parallel arrangements (E_d 2.6 Wh kg^{−1} and P_d 521 Wh kg^{−1}) rather than in series arrangements (E_d 1.8 Wh kg^{−1} and P_d 319 W kg^{−1}). This result is mainly associated with a reduction in the equivalent series resistance (ESR), thereby improving impedance matching with the load. This lower internal resistance reduces resistive losses and enhances effective power transfer during charge and discharge processes. Consequently, the parallel configuration allows more efficient use of stored energy, particularly under higher current demands, without increasing the gravimetric energy density. Such behavior is especially relevant for applications requiring rapid energy delivery, such as sensors, IoT devices, flexible or disposable electronics, and low-power hybrid systems, where impedance matching and power efficiency are more critical than absolute energy storage capacity.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/nano16040260/s1>, Figure S1: (a) Coin cell configuration; (b) Stainless steel SS304 Split Test Cell; Figure S2: (a) Commercial battery holder with plastic clips for CR2032; (b) Homemade plastic tube holder for serial coins; Figure S3: High-resolution spectrums of activated carbon PK700: (a) C_{1s}, (b) O_{1s} and (c) N_{1s}, and modified carbon PK700N: (d) C_{1s}, (e) O_{1s} and (f) N_{1s}; Figure S4: High-resolution spectrums of activated carbon PZ700: (a) C_{1s}, (b) O_{1s} and (c) N_{1s}, and modified carbon PZ700N: (d) C_{1s}, (e) O_{1s} and (f) N_{1s}; Figure S5: Charge/discharge curves at 10 s and 20 s at 0.5 V for coin cells PK700coin30. Table S1: Binding energies for functional groups of C_{1s},

O_{1s}, and N_{1s} by XPS; Table S2: Gravimetric capacitances and Equivalent series resistance from EIS for electrodes PK700* and PK700N**; Table S3: Gravimetric capacitances, Equivalent series resistance, real part of the capacitance (C'), and losses of capacitance (C'') from EIS for PK700*, PK700N**, and reference commercial (RC) coins; Table S4: Gravimetric capacitances, Equivalent series resistance from EIS for PZ700 and PZ700N; Table S5: Values of individual capacitances of the coin cells at different current and voltage during 20 s.

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References

- Hassan, Q.; Algburi, S.; Sameen, A.Z.; Salman, H.M.; Jaszczur, M. A Review of Hybrid Renewable Energy Systems: Solar and Wind-Powered Solutions: Challenges, Opportunities, and Policy Implications. *Results Eng.* **2023**, *20*, 101621. [\[CrossRef\]](#)
- Rana, M.M.; Uddin, M.; Sarkar, M.R.; Meraj, S.T.; Shafiullah, G.M.; Muyeen, S.M.; Islam, M.A.; Jamal, T. Applications of Energy Storage Systems in Power Grids with and without Renewable Energy Integration—A Comprehensive Review. *J. Energy Storage* **2023**, *68*, 107811. [\[CrossRef\]](#)
- Yadlapalli, R.T.; Alla, R.K.R.; Kandipati, R.; Kotapati, A. Super Capacitors for Energy Storage: Progress, Applications and Challenges. *J. Energy Storage* **2022**, *49*, 104194. [\[CrossRef\]](#)
- Iqbal, M.F.; Nasir, F.; Shabbir, F.; Babar, Z.U.D.; Saleem, M.F.; Ullah, K.; Sun, N.; Ali, F. Supercapacitors: An Emerging Energy Storage System. *Adv. Energy Sustain. Res.* **2025**, *6*, 2400412. [\[CrossRef\]](#)
- Diez-Restrepo, A.E.; Fernandez-Corrales, J.F.; Restrepo, M.; Manrique, E.; Porras-Naranjo, T. Reactive Energy Management in Multimodal Mass Transportation Networks: Metro de Medellín Case Study. *Energies* **2026**, *19*, 578. [\[CrossRef\]](#)
- Lakshmi, K.C.S.; Vedhanarayanan, B. High-Performance Supercapacitors: A Comprehensive Review on Paradigm Shift of Conventional Energy Storage Devices. *Batteries* **2023**, *9*, 202. [\[CrossRef\]](#)
- Torrarrit, P.; Poompradub, S.; Mohammadifar, M.; Pattananuwat, P.; Jayaraman, T.; Jeong, Y.; Chanlek, N.; Choi, M.Y.; Kasemchainan, J. Highly Porous Activated Carbon from Betel Palm Shells as the Prospective Electrode for High-Performance Supercapacitors. *Mater. Sci. Energy Technol.* **2025**, *8*, 143–153. [\[CrossRef\]](#)
- Fedepalma, F. *The Oil Palm Agribusiness in Colombia*; National Federation of Oil Palm Growers: Bogotá, Colombia, 2019; ISBN 978-958-8616-88-9.
- Misnon, I.I.; Zain, N.K.M.; Rajan, J. Conversion of Oil Palm Kernel Shell Biomass to Activated Carbon for Supercapacitor Electrode Application. *Waste Biomass Valorization* **2020**, *10*, 1731–1740. [\[CrossRef\]](#)
- Wong, P.S.; Zainal, N.H.; Foo, C.Y.; Ng, B.J.; Fong Chong, W.W.; Tan, J.P.; Wong, K.Y.; Chiong, M.C.; Mong, G.R. Fe/Co-Catalyzed Graphitization of Waste Palm Kernel Shells via One-Step Pyrolysis for Ultra-Stable EDLC Symmetrical Supercapacitor. *Energy* **2025**, *339*, 139032. [\[CrossRef\]](#)
- Paramudita, I.; Aziz, F.; Yuliantini, L.; Septina, W.; Nursam, N.M. Valorization of Oil Palm Frond into Activated Carbon Electrodes with Enhanced Electrochemical Performance for Supercapacitor. *J. Phys. Chem. Solids* **2026**, *208*, 113053. [\[CrossRef\]](#)
- Arango, D.I.; Zapata-Benabithé, Z.; Erika, C.A.; Perez-Osorno, J.C. Influence of Surface Modification with Nitric Acid on Electrochemical Performance of Agroindustrial Waste-Based Activated Carbon. *J. Mater. Sci. Mater. Electron.* **2018**, *29*, 15557–15569. [\[CrossRef\]](#)

13. Thommes, M.; Kaneko, K.; Neimark, A.V.; Olivier, J.P.; Rodriguez-Reinoso, F.; Rouquerol, J.; Sing, K.S.W.W. Physisorption of Gases, with Special Reference to the Evaluation of Surface Area and Pore Size Distribution (IUPAC Technical Report). *Pure Appl. Chem.* **2015**, *87*, 1051–1069. [[CrossRef](#)]
14. Kim, B.K.; Sy, S.; Yu, A.; Zhang, J. Electrochemical Supercapacitors for Energy Storage and Conversion. In *Handbook of Clean Energy Systems*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2015; pp. 1–25. [[CrossRef](#)]
15. Taberna, P.; Simon, P.; Fauvarque, J. Electrochemical Characteristics and Impedance Spectroscopy Studies of Carbon-Carbon Supercapacitors. *J. Electrochem. Soc.* **2003**, *150*, A292–A300. [[CrossRef](#)]
16. Diallo, A.D.D.; Alkhatib, M.F.R.; Alam, Z.M.D.; Mel, M. Municipal Solid Waste and Palm Kernel Shell Mixture As Feedstock in The Gasification Process. *Biol. Nat. Resour. Eng. J.* **2021**, *5*, 1–12. [[CrossRef](#)]
17. Lori, J.A.; Afolabi, L.; Lawal, A.O. Proximate and Ultimate Analyses of Palm Kernel Shell as Precursor for Activated Carbon. *J. Harmon. Res. Eng.* **2017**, *5*, 181–186.
18. Acevedo, J.C.; Solano, S.P.; Durán, J.M.; Posso, F.R.; Arenas, E. Estimation of Potential Hydrogen Production from Palm Kernel Shell in Norte de Santander, Colombia. *J. Phys. Conf. Ser.* **2019**, *1386*, 012093. [[CrossRef](#)]
19. Yanti, R.N.; Hambali, E.; Pari, G.; Suryani, A. The Characteristics of Palm Oil Plantation Solid Biomass Wastes as Raw Material for Bio Oil. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *141*, 012038. [[CrossRef](#)]
20. Edmund, C.O.; Christopher, M.S.; Pascal, D.K. Characterization of Palm Kernel Shell for Materials Reinforcement and Water Treatment. *J. Chem. Eng. Mater. Sci.* **2014**, *5*, 1–6. [[CrossRef](#)]
21. D3302M-19; Standard Test Method for Total Moisture in Coal. ASTM International: West Conshohocken, PA, USA, 1993.
22. D3173/D3173M-25; Standard Test Method for Moisture in the Analysis Sample of Coal and Coke. ASTM International: West Conshohocken, PA, USA, 2025.
23. D3175-20; Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke. ASTM International: West Conshohocken, PA, USA, 2020.
24. D3174-12; (Reapproved 2018). Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal. ASTM International: West Conshohocken, PA, USA, 2018.
25. D3171-22; Standard Test Methods for Constituent Content of Composite Materials. ASTM International: West Conshohocken, PA, USA, 2022.
26. D3173/D3173M-17; Standard Test Method for Moisture in the Analysis Sample of Coal and Coke. ASTM International: West Conshohocken, PA, USA, 2017.
27. D4239-18; Standard Test Method for Sulfur in the Analysis Sample of Coal and Coke Using High-Temperature Tube Furnace Combustion. ASTM International: West Conshohocken, PA, USA, 2018.
28. D5865/D5865M-19; Standard Test Method for Gross Calorific Value of Coal and Coke. ASTM International: West Conshohocken, PA, USA, 2019.
29. D1106-21; Standard Test Method for Acid-Insoluble Lignin in Wood. ASTM International: West Conshohocken, PA, USA, 2021.
30. Yacob, A.R.; Muda, N.W.; Zaki, M.A.b.M. Kesan Satu Langkah Pengaktifan KOH Terhadap Karbon Terubahsuai Dalam Tindak Balas Transesterifikasi Dengan Dimetil Karbonat. *Malays. J. Anal. Sci.* **2017**, *21*, 820–829. [[CrossRef](#)]
31. Mims, C.A. Catalytic Gasification of Carbon: Fundamentals and Mechanism. In *Fundamental Issues in Control of Carbon Gasification Reactivity*; Springer: Dordrecht, The Netherlands, 1991; pp. 383–407.
32. Elmouwahidi, A.; Bailón-García, E.; Pérez-Cadenas, A.F.; Maldonado-Hódar, F.J.; Carrasco-Marín, F. Activated Carbons from KOH and H₃PO₄ Activation of Olive Residues and Its Application as Supercapacitor Electrodes. *Electrochim. Acta* **2017**, *229*, 219–228. [[CrossRef](#)]
33. Ternero-Hidalgo, J.J.; Rosas, J.M.; Palomo, J.; Valero-romero, M.J.; Ternero-hidalgo, J.J.; Rosas, J.M.; Rodríguez-Mirasol, J.; Cordero, T. Functionalization of Activated Carbons by HNO₃ Treatment: In Fluence of Phosphorus Surface Groups. *Carbon* **2016**, *101*, 409–419. [[CrossRef](#)]
34. Puziy, A.M.; Poddubnaya, O.I.; Socha, R.P.; Gurgul, J.; Wisniewski, M. XPS and NMR Studies of Phosphoric Acid Activated Carbons. *Carbon* **2008**, *46*, 2113–2123. [[CrossRef](#)]
35. Inal, I.I.G.; Holmes, S.M.; Banford, A.; Aktas, Z. The Performance of Supercapacitor Electrodes Developed from Chemically Activated Carbon Produced from Waste Tea. *Appl. Surf. Sci.* **2015**, *357*, 696–703. [[CrossRef](#)]
36. Hulicova-Jurcakova, D.; Seredych, M.; Lu, G.Q.; Bandosz, T.J. Combined Effect of Nitrogen- and Oxygen-Containing Functional Groups of Microporous Activated Carbon on Its Electrochemical Performance in Supercapacitors. *Adv. Funct. Mater.* **2009**, *19*, 438–447. [[CrossRef](#)]
37. Wei, Y.M.; Kumar, K.D.; Zhang, L.; Li, J.F. Pseudocapacitive Materials for Energy Storage: Properties, Mechanisms, and Applications in Supercapacitors and Batteries. *Front. Chem.* **2025**, *13*, 1636683. [[CrossRef](#)]
38. Zapata, Z.; Arenas, E.; Borrás, D.; Herrera Penagos, S.N. Improvement of Electrochemical Capacitance of Activated Carbon Electrodes from African Palm Shell Modified with HNO₃. *ECS Trans.* **2021**, *100*, 27–35. [[CrossRef](#)]

39. Raymundo-Piñero, E.; Kierzek, K.; Machnikowski, J.; Béguin, F. Relationship between the Nanoporous Texture of Activated Carbons and Their Capacitance Properties in Different Electrolytes. *Carbon* **2006**, *44*, 2498–2507. [[CrossRef](#)]
40. Nasser, R.; Tiantian, J.; Song, J.M. Hierarchical Porous Activated Carbon Derived from Olives: Preparation, (N, S) Co-Doping, and Its Application in Supercapacitors. *J. Energy Storage* **2022**, *51*, 275. [[CrossRef](#)]
41. Elmouwahidi, A.; Zapata-Benabith, Z.; Carrasco-Marín, F.; Moreno-Castilla, C. Activated Carbons from KOH-Activation of Argan (*Argania spinosa*) Seed Shells as Supercapacitor Electrodes. *Bioresour. Technol.* **2012**, *111*, 185–190. [[CrossRef](#)]
42. Gamby, J.; Taberna, P.L.; Simon, P.; Fauvarque, J.F.; Chesneau, M. Studies and characterisations of various activated carbons used for carbon/carbon supercapacitors. *J. Power Sources* **2001**, *101*, 109–116. [[CrossRef](#)]
43. Conway, B. *Electrochemical Supercapacitors Scientific Fundamentals and Technological Applications*; Kluwer Academic: New York, NY, USA, 1996.
44. Bhat, T.S.; Patil, P.S.; Rakhi, R.B. Recent Trends in Electrolytes for Supercapacitors. *J. Energy Storage* **2022**, *50*, 104222. [[CrossRef](#)]
45. Tobi, A.R.; Dennis, J.O. Activated Carbon from Composite of Palm Bio-Waste as Electrode Material for Solid-State Electric Double Layer Capacitor. *J. Energy Storage* **2021**, *42*, 103087. [[CrossRef](#)]

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