

# Unlocking High Energy and Power Densities in Supercapacitors: The Role of Moisture Content in Coconut Shell Pulverized Activated Carbon Electrodes

I.I. Ajibade & L. Sa'adu

Department of Physics, Federal University Gusau, Zamfara State, Nigeria

Corresponding Author's Email: [isaajibade@fugusau.edu.ng](mailto:isaajibade@fugusau.edu.ng)

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## ABSTRACT

This study explores the potential of coconut shells as a sustainable source for supercapacitor electrodes. Electrochemical characterization revealed pseudocapacitive behavior with a specific capacitance of 15.57 F/g. Interestingly, samples derived from coconut shells with higher moisture content displayed superior energy and power densities, reaching 1.38 Wh/kg and 498,312 W/kg, respectively, as measured by cyclic voltammetry. These findings highlight the crucial role of moisture in enhancing the electrochemical performance of coconut shell electrodes. The utilization of coconut shells from humid regions presents a promising strategy for developing high-performance supercapacitors that offer both excellent energy storage and extended lifespan.

**Keywords:** Coconut Shells, Cyclic Voltammetry Electrodes Energy Density High-Performance Power Density Pseudocapacitive

## 1.0 INTRODUCTION

Limited sources of fossil fuels along with growing population and technology development put the mankind in front of an energy problem (Elavarasan *et al.*, 2020). Increasing pollution forces us to think about energy and the approach to energy management. Energy systems play a key role in harvesting energy from various sources and converting it to the energy forms required for applications in various sectors, for example utility, industry, building and transportation (Kalair *et al.*, 2021). Fossil fuels provide on-demand energy due to easy storage, but renewable sources like solar and wind require harvesting during availability and storage for later use Karaca and Dincer (2021).

Energy storage systems play an important role in a diverse range of industrial applications as either bulk energy storage or distributed transient energy buffer (Sikiru *et al.*, 2024). Specific energy, specific power, lifetime, reliability, and safety are among the main criteria considered when picking energy storage (Khan *et al.*, 2019). Rechargeable batteries, especially lithium-ion batteries, are currently a popular option due to their high energy density and acceptable cycle life (Shen *et al.*, 2018). Nevertheless, they have limits of relatively low power density and relatively high internal resistance that could heavily curtail their power-delivery capability under large current loading (Zhang *et al.*, 2018). Moreover, battery life is highly susceptible to high current-rate and transient loading conditions (Wang *et al.*, 2022). In order to overcome these shortcomings, redundant design is often adopted in practice for pulse

and peak power fulfillment, which inevitably incurs additional expense. On the other hand, supercapacitors (SCs), also known as ultracapacitors (UCs) or Electric Double-Layer Capacitors (EDLCs), are being actively studied and unanimously envisaged as a promising energy storage technology, owing to their desirable merits including high-power density and high degree of recyclability (Zhang *et al.*, 2018). They have additional advantages, such as low internal resistance, wide operating temperature window, and high efficiency Zhao and Burke (2021). These advantageous characteristics render them particularly suitable for working independently or in tandem with other high-energy devices for power sinking/sourcing in real plants. Supercapacitors are governed by the same fundamental equations as conventional capacitors but utilize higher surface area electrodes and thinner dielectrics to achieve greater capacitance (Da Silva *et al.*, 2020). This allows for energy densities greater than those of conventional capacitors and power densities greater than those of batteries (Gao *et al.*, 2023). As a result, supercapacitors have become an attractive power solution for an increasing number of applications. Supercapacitors are used in applications, where is the need to store or release huge amount of energy in a very short time (Mathuria *et al.*, 2024). Nowadays, the supercapacitors are used primarily in Hybrid Electric Vehicles (HEV), Electric Vehicles (EV) and Fuel Cell Vehicles (FCV) like passenger car strains, trolleybuses (Zheng *et al.*, 2021). Another area of supercapacitors' use are electronic devices as Uninterruptible Power Supplies (UPS) and volatile memory backups in PCs (Dutta *et al.*, 2023). It is equally use in energy harvesting systems, solar arrays, or

wind turbines, where supercapacitors play a supplementary role next to conventional batteries (Zhou *et al.*, 2021).

The obstacles faced by super capacitors are many and include Ohmic leakage, self-discharged, charge distribution, mass loading, temperature dependence, matching application, electrolyte optimization, material selection, and pore structure, even with all these historic accomplishments Babu (2024). The performance of supercapacitors strongly depends on the morphology of the electrode materials, current collectors, electrolytes, and separators (Ghafoor *et al.*, 2024). In particular the morphology of the electrodes is crucial since the amount of charge stored is proportional to the effective surface area of the carbon material Platek-Mielczarek *et al.* (2024). An ideal electrode material is therefore expected to exhibit high surface area, high porosity, homogeneous pore size distribution, and high electrical conductivity, as well as having a low production cost (Zhang *et al.*, 2024). Consequently, there need to consider factors, such as the level of moisture, which is influenced by relative humidity, as well as the age and type of coconut shells, is crucial when evaluating the potential suitability of coconut shells as a raw material for producing activated carbon. This is especially important when considering their use in the creation of supercapacitors.

In the current study, we utilized a chemical pulverization method to create enhanced porous carbon from coconut shells (*cocos nucifera*) sourced from various geopolitical zones. These shells had different levels of moisture content (Masthura & Abdul, 2018). Prior to the activation process, the coconut shells underwent treatment with concentrated sulfuric acid ( $H_2SO_4$ ). This treatment has been shown to effectively hydrolyze and oxidize materials, leading to the introduction of a significant number of functional groups on the carbon surface. These functional groups include carboxyl, lactone, phenolic, sulfur, and others. It has been established that these functional groups play a role in enhancing the efficiency of both non-faradaic and faradaic processes associated with electron and charge transfer.

## 2.0 THEORETICAL BACKGROUND

### 2.1 Determination of Specific Capacitance Of Super Capacitor From Cyclic Voltammetry (CV)

Cyclic voltammetry is an electrochemical technique in which the potential is swept repeatedly for example, between a start and end potential and the resulting currents are measured. What makes voltammetry beneficial in many systems is the diversity of information a single scan can provide about the system's behavior, such as the absorption-desorption process at the electrode surface. This section explores the core mathematical

principles, material attributes, and operational mechanisms that dictate the application of activated carbon in supercapacitors. A supercapacitor, also known as an ultracapacitor, is a high-capacity capacitor that stores and releases energy much faster than batteries, with a capacitance value significantly higher than conventional capacitors (Valarmathi *et al.*, 2024). Conventional capacitors consist of two conducting electrodes separated by an insulating dielectric material. When a voltage is applied to a capacitor, opposite charges accumulate on the surfaces of each electrode. The charges are kept separate by the dielectric, thus producing an electric field that allows the capacitor to store energy. Capacitance  $C$  is defined as the ratio of stored (positive) charge to the applied voltage.

$$C = \frac{Q}{V} \quad (1)$$

For a conventional capacitor, the capacitance is directly proportional to the surface area  $A$  of each electrode and inversely proportional to the distance  $D$  between the electrodes.

$$C = \epsilon_0 \epsilon_r \frac{A}{D} \quad (2)$$

where  $\epsilon_0$  is the electric constant (or permittivity) of free space and  $\epsilon_r$  is the dielectric constant (or relative permittivity) of the insulating material between the electrodes. The product of the first two factors on the right-hand side of equation (2) is a constant of proportionality. Two important attributes of a supercapacitor are its energy density and power density. For either measure, the density can be calculated as a quantity per unit mass or per unit volume.

Specific capacitance from Cyclic Voltammetry

$$C_s = \frac{Q}{mv} \quad (3)$$

where  $Q$  is the charge in (coulombs),  $m$  is the mass of the active material (g),  $v$  is the potential in mV, and  $C_s$  is the specific capacitance in F/g

But

$$Q = It, \quad (4)$$

Therefore,

$$C_s = \frac{It}{mv} \quad (5)$$

dividing through by  $t$

$$C_s = \frac{It/t}{mv/t} \quad (6)$$

Where  $\left(\frac{V}{t}\right)$  is the scan rate of the cyclic voltammetry and represented by  $k$

In cyclic voltammetry (CV), scan rate refers to the rate of change of the applied voltage over time during the experiment.

$$C_s = \frac{I}{mk} \quad (7)$$

$$I = C_s \times m \times k \quad (8)$$

However, in Cyclic Voltammetry (CV), the voltage and current variations are said to be periodic. therefore, equation (8) can be represented in the integral form as,

$$\int_{v_1}^{v_2} I(v)dv = \int_{v_1}^{v_2} (C_s \times m \times k)dv \quad (9)$$

Where  $\int_{v_1}^{v_2} I(v)dv$  is the area of the CV curve,

$$\text{therefore, } A = \int_{v_1}^{v_2} (C_s \times m \times k)dv.$$

For a specific substance, specific capacitance  $C_s$ ,  $m$  and  $k$  are constant, therefore,

$$A = C_s \times m \times k \int_{v_1}^{v_2} (dv) \quad (10)$$

$$\text{Area} = [v_2 - v_1]C_s \times m \times k \quad (11)$$

It can be shown from equation (11) that,

$$C_s = \frac{A}{2[v_2 - v_1] \times m \times k} \quad (\text{Sami et al., 2018}) \quad (12)$$

$$C_s = \frac{A}{2 \times m \times k [v_2 - v_1]} \quad (13)$$

Where  $C_s$  is the specific capacitance in F/g, A is the Area inside the CV in AV, m is the mass of the active material, k is the constant scan rate of CV in volts per seconds and  $(v_2 - v_1)$  is the potential window of the CV.

## 2.2 Energy Density and Power Density from Specific Capacitance Using Cyclic Voltammetry Curve

The energy E stored in a capacitor is directly proportional to its capacitance as shown

$$E = \frac{1}{2} C v^2 \quad (15)$$

$$E = \frac{\Delta V^2 \times C_s}{2 \times 3.6} \quad (\text{Sethi et al., 2020}) \quad (16)$$

$$p = \frac{E}{\Delta t} \times 3600 \quad (\text{Sethi et al., 2020}) \quad (17)$$

Where E is the energy density in (Wh kg<sup>-1</sup>), and p is the power density in (W kg<sup>-1</sup>) representing equations (16) and (17) respectively.

## 2.3 Difference Between Mass Density and Energy Density (Storage Devices)

Mass density and energy density are shown in table 2.9. There is always a misconception about them. Mass density, measured in kilograms per cubic meter (kg/m<sup>3</sup>), describes how tightly packed the matter is in a substance.

**Table 2.9: Showing the differences between Mass density and Energy density**

Property	Mass Density	Energy Density
What it measures	Mass per unit volume	Energy per unit volume
Symbol	ρ (rho)	E (varies depending on the type of energy)
Units	kg/m <sup>3</sup> (kilograms per cubic meter)	Wh/Kg (Watt-hours per kilogram)
Interpretation	How tightly packed the matter is in a substance	How much electrical energy can be stored per kilogram of a substance
Example	Water: 1000 kg/m <sup>3</sup>	Lithium-ion battery: 250 Wh/Kg (typical value)
Dependence	Depends on the material	Depends on the material and its ability to store electrical energy
Relevance	Useful for understanding buoyancy, packing efficiency, and material properties	Important for battery performance, portability of electronic devices, and electric vehicle range

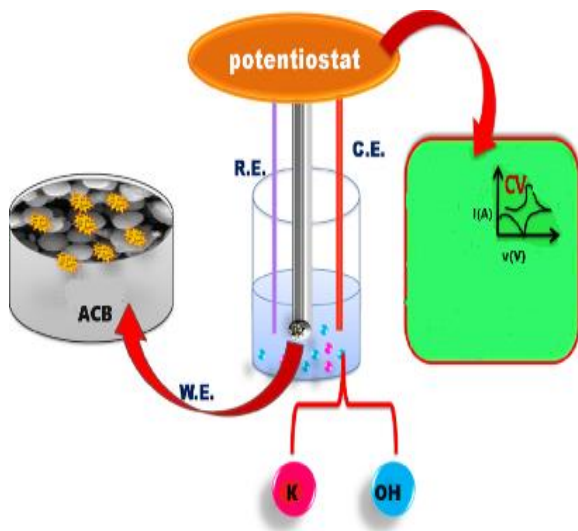
In contrast, energy density, given in Watt-hours per kilogram (Wh/Kg), reflects how much energy, specifically electrical energy in this case, can be stored within a kilogram of that material. For instance, water has a high normal density (1000 kg/m<sup>3</sup>), but it cannot store electrical energy. Conversely, a Lithium-ion battery might have a lower normal density but boasts a significant energy density of around 250 Wh/Kg, making it crucial for powering portable electronics and electric vehicles where weight and energy storage capacity are both important factors.

## 3.0 MATERIALS AND METHODS

### 3.1 Device Fabrication and Measurement

The electrodes for the electrochemical studies were prepared by mixing the dried ACB (70mg.) with conducting carbon (Super P, 15mg) and polyvinylidene fluoride (PVDF, 15mg)) binder using N-methylpyrrolidinone (NMP) as a solvent. The above mixture was stirred overnight, and the slurry obtained thereby was coated on top re-cleaned nickel foam (pores per inch; 110ppi) substrate. The coated electrode was annealed at 170°C in an oven for 20 h. The blank carbon cloth was weighed before loading and reweigh after loading and dried. All electrodes were controlled to have ~1 cm<sup>2</sup> contact area with mass loading ~3mg. The electrochemical properties were evaluated by Cyclic Voltammetry (CV). The CV were obtained in the

potential range of 0.8–0.0 V at various scan rates in three-electrode configuration using a potentiostat-galvanostat (Autolab PGSTAT 30, Eco Chemie B.V., Malaysia), with potassium hydroxide (KOH) as electrolyte. All the electrochemical measurements were performed using the Autolab potentiostat using platinum as the counter electrode and Ag/AgCl as the reference electrode.



**Plate 1. Measurement of specific capacity through Cyclic Voltammetry**

A three-electrode setup is the preferred method for cyclic voltammetry (CV) experiments due to its ability to isolate the behavior of the working electrode. In a three-electrode system, the following electrodes are used:

### 3.1.1 Working Electrode (WE)

This is the electrode where the electrochemical reaction of interest occurs. The potential of the working electrode is actively controlled by the potentiostat.

### 3.1.2 Counter Electrode (CE)

This electrode completes the electrical circuit and balances the current passed through the working electrode. The counter electrode itself ideally does not undergo any significant electrochemical reactions within the potential window of the experiment.

### 3.1.3 Reference Electrode (RE)

This electrode provides a stable and well-defined potential reference for the working electrode. The potential difference between the working and reference electrodes is what the potentiostat measures. The working electrode is connected to the terminals of the potentiostat. This allows for independent measurement of the current flowing through the working electrode. The counter electrode is connected to the counter electrode

(CE) terminal of the potentiostat. The reference electrode is connected to the reference electrode (RE) terminal of the potentiostat. In a CV experiment, the potentiostat starts by applying a starting potential to the working electrode. The potentiostat then scans the potential of the working electrode linearly at a constant scan rate towards a first vertex potential. Once the first vertex potential is reached, the scan direction is reversed, and the potential is scanned back towards the starting potential or a second vertex potential.

Throughout the potential scan, the current flowing between the working electrode and the counter electrode is measured. The resulting current versus potential plot is the cyclic voltammogram, which provides valuable information about the electron transfer processes occurring at the working electrode. By analyzing the peak currents, peak potentials, and the overall shape of the voltammogram, the specific capacitance can be measured.

## 4. RESULTS AND DISCUSSIONS

The result of this experiment is on the use of activated carbon derived from coconut shells in supercapacitors. Supercapacitors are a type of energy storage device that can store more energy than traditional capacitors but less than batteries. They are known for their ability to deliver power quickly.

The experiment investigated the effect of moisture content in the coconut shells on the performance of the supercapacitors. We prepared activated carbon samples from coconut shells with different moisture contents. We then measured the surface area, capacitance, energy density, and power density of the activated carbon samples.

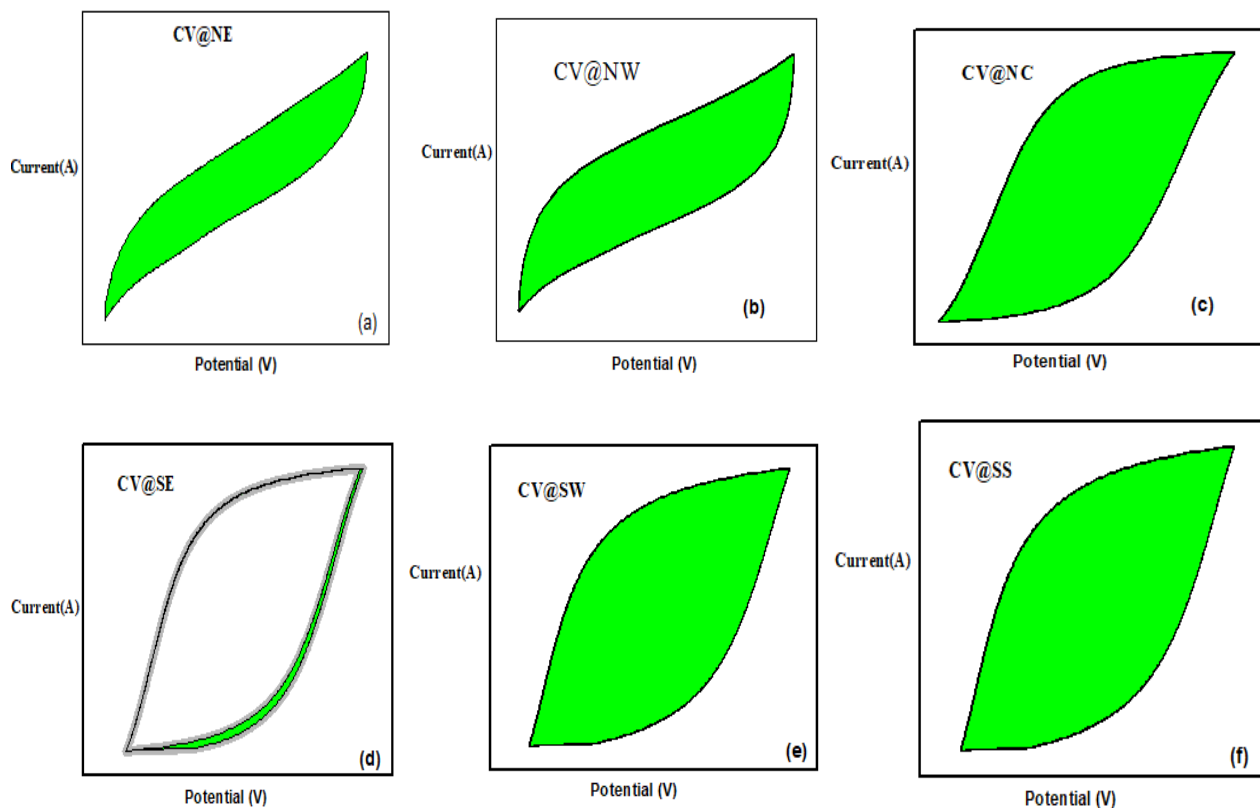
The results shows that the samples with higher moisture content had higher capacitance, energy density, and power density as confirmed through the graph of the cyclic voltammetry. This suggests that moisture content plays an important role in the performance of supercapacitors made from activated carbon derived from coconut shells.

In Cyclic Voltammetry (CV) the specific capacitance  $C_s$  is given as,

$$C_s = \frac{I dt}{m_{el} dV} \quad (\text{Kigozi et al., 2020})$$

where,  $C_s$  is the specific capacitance (F/g),  $I$  is the discharge current (A),  $m_{el}$  is the total mass of active materials (g),  $dv$  is the change in discharge voltage (v) and  $dt$  the change in discharge time (s). The results of the setups made from the ACB (NW, NE, NC, SW, SE, SS at

850 °C) samples were analyzed with Potassium hydroxide electrolyte. In the assessment of the cyclic voltammetry, the voltammograms electrolytes were obtained using 10mV/s scan rate, 0.003g representing the mass of the active material and potential window of 0.8V. All six-electrode materials display leaflike shape as shown in figure 2. These characteristics can be assigned to Pseudo capacitor as MPK having heteroatoms were doped with the ACB.



**Figure 1. Cyclic Voltammetry Curve for ACB in a, b, c, d, e, and f corresponding to NE@850 °C, NW@850 °C, NC@850SW@850 °C, SE@850 °C and SS@850 °C respectively.**

Table 1 and 2 summarize the properties of six activated carbon samples prepared in an inert atmosphere. It details their BET surface area (measured using the Brunauer-Emmett-Teller technique), capacitance, energy density, power density, and along both low and moisture content. The data reveals a positive correlation between BET surface area and the three-performance metrics: capacitance, energy density, and power density. Notably, sample SS at 850 °C boasts the highest surface area (13.3512 m<sup>2</sup>/g) and the strongest performance across all three categories (capacitance: 15.57 F/g, energy density: 1.38 Wh/Kg, power density: 498,312 W/Kg). Conversely, sample NE@850 °C, with the lowest surface area (0.72779 m<sup>2</sup>/g), also exhibits the weakest capacitance (0.8628 F/g). This further proved the effect of moisture in optimizing a hierarchical porous route in activated carbon.

**Table 1. Area generated from the Cyclic Voltammetry (CV)**

Samples	Surface Area From (CV) $\times 10^{-4} \text{AV}$	Specific Capacitance ( $C_s$ ) F/g
NE	0.414	0.863
NW	0.708	1.476
NC	1.565	3.261
SE	4.616	9.617
SW	6.974	14.53
SS	6.474	15.57

**Table 2. BET surface area, capacitance, energy density and power density of activated carbon prepared in inert**

Samples	BET ( $\text{m}^2/\text{g}$ )	Specific Capacitance ( $C_s$ ) (F/g)	Energy Density (Wh/Kg)	Power Density (W/Kg)	R/H(%)
NE at 850 °C	0.2779	0.863	0.077	27,612	35
NW at 850 °C	0.7099	1.476	0.131	47,239	38
NC at 850 °C	4.2035	3.261	0.289	104,370	65
SE at 850 °C	11.5064	9.617	0.855	307,756	81
SW at 850 °C	13.1211	14.539	1.292	464,984	85
SS at 850 °C	13.3512	15.572	1.384	498,312	85

## 5.0 CONCLUSION

This study highlights the need to consider factors, such as the level of moisture content, which is influenced by relative humidity, as well as the age and type of coconut shell alongside traditional factors like temperature during activated carbon production. While higher humidity generally increases moisture content, it unexpectedly resulted in a larger surface area for samples carbonized at higher temperatures. This newfound knowledge strengthens the observed positive correlation between BET surface area and performance metrics like capacitance, energy density, and power density. Sample SS at 850 °C exemplifies this connection, boasting the highest surface area and superior performance across all six categories. For example, the sample from the SS region, which has the highest BET surface area (13.1211  $\text{m}^2/\text{g}$ ), specific capacitance (14.539 F/g), energy density (1.384 Wh/Kg), and power density (498,312 W/Kg) followed by SW (BET surface area 13.1211  $\text{m}^2/\text{g}$ ), specific capacitance (14.539 F/g), energy density (1.29 Wh/Kg), and power density (464,984 W/Kg)). This suggests that there is a positive correlation between the relative humidity of the sampling location and the performance of the activated carbon samples. Conversely, sample NE at 850°C, has the lowest relative humidity of 35% with the lowest BET surface area (0.2779  $\text{m}^2/\text{g}$ ), specific capacitance (0.863 F/g), energy density (0.077 Wh/Kg), and power density (27,612 W/Kg), also demonstrated the weakest capacitance. These findings suggest that controlled

moisture content can be leveraged to optimize the formation of hierarchical pores within the activated carbon structure. This research opens doors for cost-effective and diverse applications by demonstrating the potential for optimizing activated carbon production from readily available coconut shells, considering both humidity and traditional parameters. Furthermore, the study successfully achieved its goals by creating activated carbon samples from various Nigerian regions, analyzing their properties, and evaluating their morphology and porosity at different pulverization temperatures.

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