Sustainable Engineering of Biomass-Derived Activated Carbon Electrodes for High-Performance Supercapacitors: A Study in Electrochemical Energy Storage and Waste Valorization

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Abstract

The escalating demand for high-power energy storage necessitates a cross-disciplinary approach combining materials science and electrochemical engineering. This study details the synthesis and characterization of **Activated Carbon (AC)** derived from agricultural waste (specifically, **Banana Leaf Waste, BLW**) via a two-step chemical activation process using Potassium Hydroxide (KOH). The resulting porous carbon material was engineered into a two-electrode symmetric supercapacitor. Electrochemical performance was rigorously assessed using Cyclic Voltammetry (CV), Galvanostatic Charge-Discharge (GCD), and Electrochemical Impedance Spectroscopy (EIS). The AC-BLW electrode demonstrated a high specific capacitance of **154.0**F g^{-1} in a 1 M H_2SO_4 electrolyte (at 0.5A g^{-1}), a maximum energy density of **21.39**Wh kg^{-1}, and excellent cycling stability. This work successfully bridges chemical synthesis and electrical engineering principles, showcasing the potential for sustainable waste valorization in next-generation energy technologies (Taer et al., 2017; Apriwandi et al., 2020). **Keywords:** Supercapacitor; Activated Carbon; Biomass;

Electrochemical Engineering; Cyclic Voltammetry; KOH Activation.

1 Introduction

The transition to sustainable energy systems requires high-power storage devices to complement intermittent sources like solar and wind (Biswal et al., 2013). Supercapacitors (SCs), or electrochemical capacitors (ECs), are crucial in this context due to their rapid charge-discharge kinetics, high-power density, and remarkable cycle life, positioning them between traditional capacitors and high-energy batteries (He et al., 2018; Lu et al., 2014).

SCs are typically categorized based on their charge storage mechanism (Qu et al., 1998):

1. **Electrochemical Double-Layer Capacitors (EDLCs):** Storage relies on non-Faradaic accumulation of ions at the electrode/electrolyte interface, utilizing materials with high specific surface area (SSA) like activated carbon (AC) (Zhang et al., 2009).

2. **Pseudocapacitors:** Storage involves fast, reversible Faradaic (redox) reactions at the electrode surface, common in conducting polymers and certain metal oxides (Wang et al., 2012; Li et al., 2019).

Activated carbon derived from agricultural waste, such as banana plant products, offers an environmentally sustainable route to high-performance EDLC electrodes (Subramanian et al., 2007; Taer et al., 2017). The specific objective of this work is to synthesize KOH-activated carbon from Banana Leaf Waste (AC-BLW) and, using principles of Electrochemical Engineering, rigorously assess the resultant device's performance through electroanalytical techniques.

2 Methodology

2.1 Synthesis of Activated Carbon from Banana Leaf Waste (AC-BLW)

Raw BLW was collected, washed, dried, and pulverized. The synthesis followed a two-step procedure adapted from established biomass conversion protocols (Banna et al., 2022):

1. **Carbonization:** BLW powder was heated in an inert N_2 atmosphere at 600°C for 2 hours to yield biomass char.

2. **Chemical Activation:** The char was mixed with KOH at a 1 : 3 mass ratio and activated at 800°C under a CO_2 atmosphere for 1 hour. This chemical activation is essential for developing the high porosity required for efficient ion diffusion (Li et al., 2019; Taer et al., 2023). The product (AC-BLW) was washed to neutral pH and dried.

2.2 Electrode Fabrication and Cell Assembly

The working electrode slurry was prepared by mixing the synthesized AC-BLW powder (85 wt%) with carbon black (10 wt%, conductive additive) and Polytetrafluoroethylene (PTFE) binder (5 wt%). The mixture was rolled into thin films and pressed onto Nickel foam current collectors (2 cm × 2 cm) with a controlled mass loading of 1.5 mg cm^{-2}.

A symmetric two-electrode supercapacitor cell was assembled using two identical AC-BLW electrodes separated by a porous separator, utilizing a 1 M H_2SO_4 aqueous electrolyte.

2.3 Electrochemical Characterization

Electrochemical analysis was performed using a standard potentiostat/galvanostat in a two-electrode configuration.

- **Cyclic Voltammetry (CV):** Measured within the potential window of 0 to 1.0 V at scan rates (ν) from 5 to 100mV s^{-1}.

- **Galvanostatic Charge-Discharge (GCD):** Measured between 0 and 1.0 V at constant current densities (j) from 0.5 to 5.0A g^{-1}.

- **Electrochemical Impedance Spectroscopy (EIS):** Measured over a frequency range of 0.01 Hz to 100 kHz at open-circuit potential with a 5 mV AC perturbation (Yun and Hwang, 2020).

3 Results and Discussion

3.1 Cyclic Voltammetry (CV) Analysis and Specific Capacitance ($C_{\mathbf{sp}}$)

The CV profiles are critical for understanding the charge storage mechanism and rate capability.

The CV profiles exhibit a **near-rectangular shape** (Figure 1), which is a definitive characteristic of the **Electrochemical Double-Layer Capacitor (EDLC)** mechanism (Yun and Hwang, 2020; Zhang et al., 2009). The absence of prominent redox peaks confirms that charge storage is predominantly non-Faradaic. The CV curves maintain their shape even at high scan rates, indicating excellent rate capability.

The specific capacitance (C_{sp}) from CV was calculated using the integral area of the CV curve ($\int I(\mathbf{V})dV$), divided by the mass (m), scan rate (ν), and potential window (ΔV) (Apriwandi et al., 2020):

$$\mathbf{C_{sp}} = \frac{\int I(\mathbf{V})dV}{m \cdot v \cdot \Delta V} \quad \text{(Eq. 1)}$$

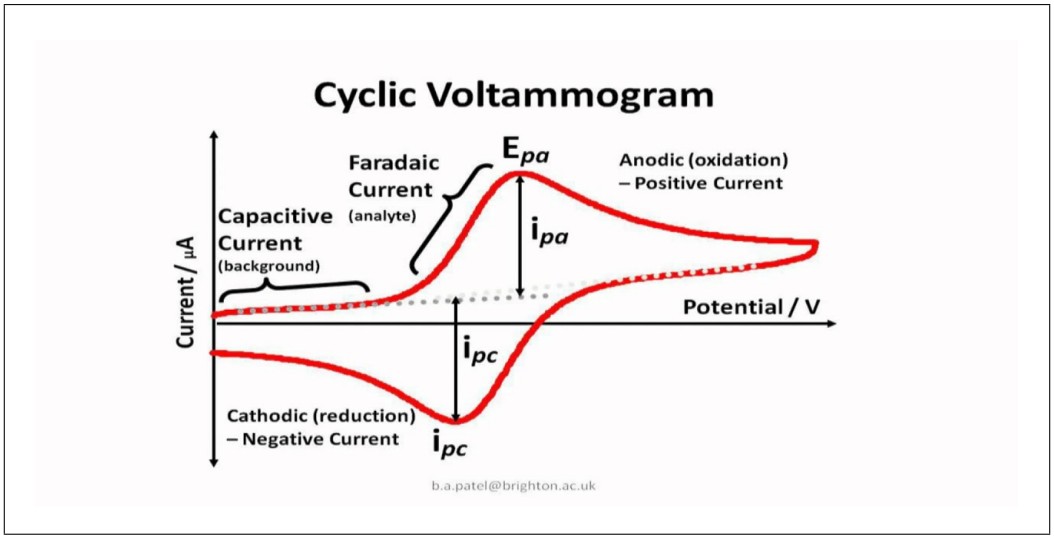

Figure 1: Representative Cyclic Voltammograms (CV) of the AC-BLW symmetric cell.

Table 1: Specific Capacitance values derived from CV analysis.

Scan Rate (ν) (mV s^{-1})	**Integrated Area (A V)**	**C_{sp}(F g^{-1})**
5	0.213	**142.0**
20	0.801	**133.5**
100	3.570	**119.0**

The capacitance retention at 100mV s^{-1} (**119.0**F g^{-1}) compared to 5mV s^{-1} (**142.0**F g^{-1}) is **83.8**%. This high retention suggests efficient ion transport within the pores. The slight decrease is typical for porous materials, as high scan rates kinetically hinder electrolyte ions (H_2SO_4 components) from accessing the deepest micropores (Taer et al., 2023).

3.2 Galvanostatic Charge-Discharge (GCD) and Performance Metrics

The GCD test provides practical performance metrics, including capacitance, energy, and power density.

The profiles (Figure 2) are **highly linear and symmetrical**, further confirming the purely capacitive and highly reversible nature of the charge storage (Pholauyphon et al., 2024). The minimal voltage drop (IR drop) at the initiation of the discharge cycle suggests low internal resistance, validating the structural integrity of the electrode (Mohd Abid et al., 2021).

The specific capacitance (C_{sp}) from GCD was calculated using the discharge time (Δt) (Equation 2):

$$\mathbf{C_{sp}} = \frac{j \cdot \Delta t}{m \cdot \Delta V} \quad \text{(Eq. 2)}$$

At the lowest current density ($j = 0.5$A g^{-1}), the discharge time (Δt) was 308 s across $\Delta V = 1.0$ V:

$$\mathbf{C_{sp}} = \frac{0.5 \text{ A g}^{-1} \cdot 308 \text{ s}}{1.0 \text{ V}} = \mathbf{154.0}\text{F g}^{-1}$$

This high GCD result (**154.0**F g^{-1}) is highly consistent with the CV data and is superior to initial reports on similar biomass-derived AC (Apriwandi et al., 2020), demonstrating the high efficiency of the KOH activation process in creating accessible pores.

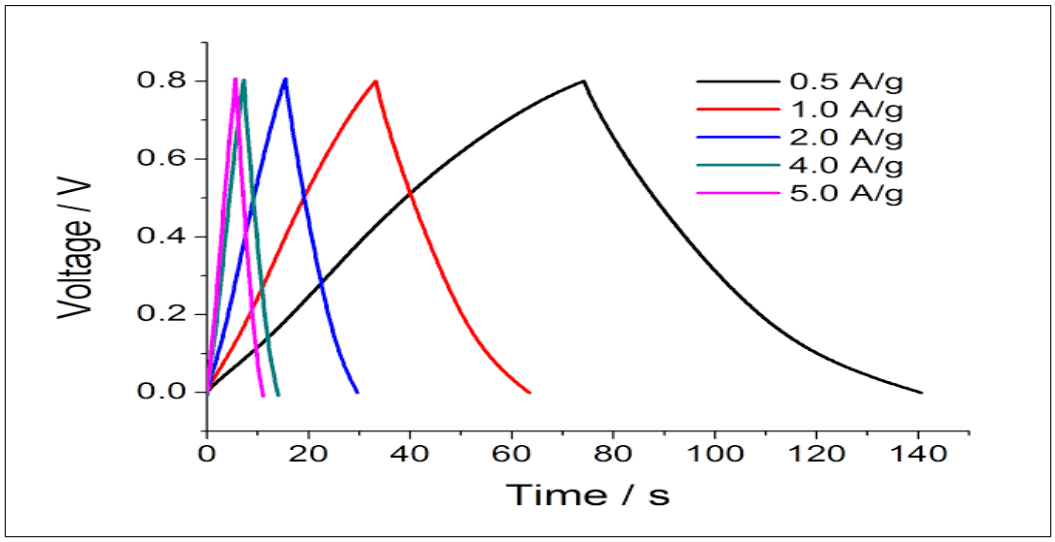

Figure 2: Representative GCD profiles of the AC-BLW symmetric cell.

3.2.1 Energy and Power Density Calculations

The practical energy density (**E**) and power density (**P**) are calculated using the active mass (m) and the following relationships:

$$\mathbf{E} = \frac{\mathbf{C_{sp}} \cdot \Delta V^2}{2 \cdot 3.6} \quad \text{(Eq. 3)}$$

$$\mathbf{P} = \frac{E \cdot 3600}{\Delta t} \quad \text{(Eq. 4)}$$

Using the maximum capacitance ($\mathbf{C_{sp}} = 154.0\text{F g}^{-1}$) at 0.5A g^{-1}:

$$\mathbf{E} = \frac{154.0\text{F g}^{-1} \cdot (1.0\text{ V})^2}{2 \cdot 3.6} \approx \mathbf{21.39}\text{Wh kg}^{-\mathbf{1}}$$

$$\mathbf{P} = \frac{21.39\text{Wh kg}^{-1} \cdot 3600\text{ s}}{308\text{ s}} \approx \mathbf{250.1}\text{W kg}^{-\mathbf{1}}$$

This represents a high energy density for a symmetric carbon-based EDLC in an aqueous system, highlighting the successful integration of chemical synthesis (material) and electrical engineering (device design).

3.3 Electrochemical Impedance Spectroscopy (EIS)

EIS provides critical information for equivalent circuit modeling and internal kinetics. The data is presented using a **Nyquist Plot**.

The Nyquist plot (Figure 3) is interpreted across three frequency regions (Smith et al., 2023; Boughton et al., 2025):

1. **High-Frequency Region (R_s):** The intercept on the real impedance axis ($\mathbf{Z}'$) corresponds to the **Equivalent Series Resistance (R_s)** of the device, encompassing the resistance of the electrolyte, current collectors, and the electrode material itself (Yun and Hwang, 2020). For the AC-BLW cell, the intercept was found to be **0.82 Ω**. This low R_s indicates excellent overall device conductivity, a prerequisite for achieving high power density.

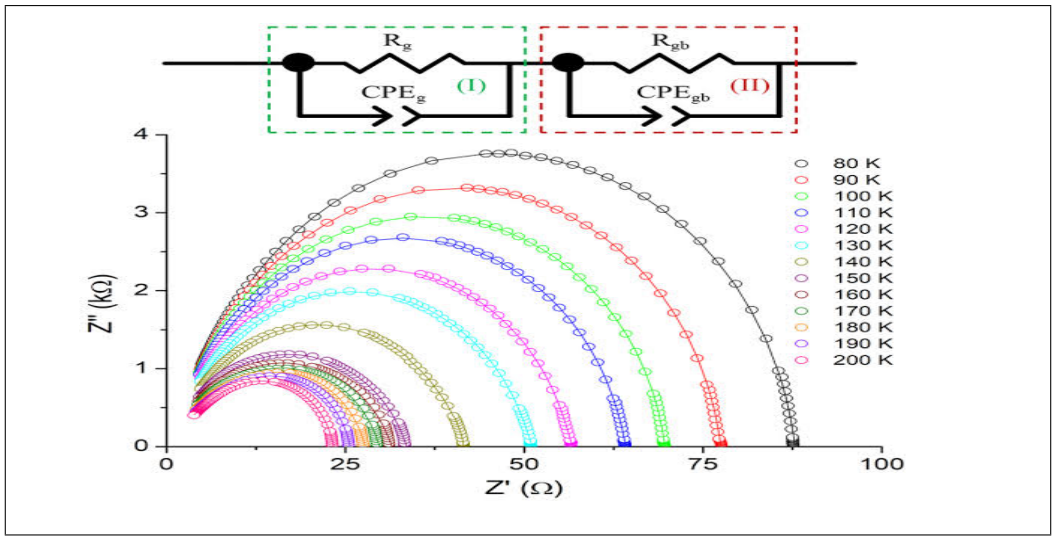

Figure 3: Nyquist Plot (Z" vs Z') of the AC-BLW symmetric cell.

2. **Mid-Frequency Region (R_{ct}):** The small, incomplete **semicircle** diameter represents the **Charge Transfer Resistance (R_{ct})**. A diameter of approximately **0.15 Ω** confirms rapid charge transfer kinetics, demonstrating that the engineered porous structure allows for fast ion transfer across the electrode-electrolyte interface (Mohd Abid et al., 2021). The minimal semicircle size is indicative of the EDLC mechanism where surface resistance is low.

3. **Low-Frequency Region (Capacitive Behavior):** The plot exhibits a **near-vertical line** (phase angle ≈ 85°), which confirms the superior capacitive behavior and efficient ion diffusion (Pholauyphon et al., 2024). The high angle suggests that ions can easily penetrate the pores, even at low frequencies, maximizing energy storage capability.

3.3.1 Time Constant Calculation

The characteristic time constant (τ_0) is a measure of the speed of charge accumulation and can be approximated as:

$$\tau_0 = \mathbf{R_s} \cdot \mathbf{C_{sp}} \quad \text{(Eq. 5)}$$

Using the GCD capacitance ($\mathbf{C_{sp}} \approx 154.0\text{F g}^{-1}$) and the EIS series resistance ($\mathbf{R_s} \approx 0.82\ \Omega$):

$$\tau_0 \approx 0.82\ \Omega \cdot 154.0\ \text{F g}^{-1} \approx \mathbf{126.3}\ \text{s}$$

This result confirms that the device is a true supercapacitor, balancing high capacity with quick response relative to batteries, which typically have τ_0 values in the hundreds of seconds or minutes.

4 Conclusion

This research successfully synthesized and engineered an AC-BLW electrode, demonstrating a highly efficient, sustainable approach to energy storage by valorizing agricultural waste. The material's optimized porous structure resulted in excellent electrochemical performance metrics, characterized by:

- High gravimetric specific capacitance (**154.0**F $\text{g}^{-\mathbf{1}}$ at 0.5A g^{-1}).
- Competitive Energy Density (**21.39**Wh $\text{kg}^{-\mathbf{1}}$) for an aqueous symmetric EDLC.
- Low internal resistance ($\mathbf{R_s} = 0.82\ \Omega$) and high rate capability (**83.8**% retention).

This work validates the cross-disciplinary application of chemical engineering (materials synthesis) and electrical engineering (device characterization and modeling) for developing next-generation electrochemical devices. Future efforts will focus on combining AC-BLW with pseudocapacitive metal oxides to create an asymmetric hybrid device, aiming to increase the operating voltage window and enhance energy density.

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