

Optimized Single-Step Carbonization of Michelia Champaca Biomass for High-Performance Supercapacitor Electrodes

Dibyashree Shrestha

shresthadibyashree@gmail.com

Tribhuvan University

Research Article

Keywords: Michelia Champaca wood, Electrochemical performance, Carbonization, Specific capacitance, Energy density, Power density, Sustainable materials

Posted Date: November 18th, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-5368152/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

This study investigates the potential of *Michelia Champaca*, a hardwood, as a sustainable precursor for high-performance supercapacitor electrodes. Activated carbons were prepared using single-step carbonization at 400°C and 500°C (SSC-400°C and SSC-500°C) and double-step carbonization at 400°C (DSC-400°C) with all samples activated using H₃PO₄. The effects of carbonization temperature on the structural, morphological, and electrochemical properties of the resulting electrodes were examined. SSC-400°C exhibited superior electrochemical performance, with a specific capacitance of 292.2 F g⁻¹, energy density of 6.4 Wh kg⁻¹, and power density of 198.4 W kg⁻¹. Its optimized pore structure and surface chemistry contributed to enhanced performance. SSC-500°C showed slightly lower performance, while DSC-400°C demonstrated the lowest, suggesting that the double-step process may negatively impact structural and electrochemical properties. These findings highlight the potential of *Michelia Champaca* wood as a renewable source for high-quality activated carbon materials suitable for supercapacitor applications. Future research could focus on optimizing the carbonization process and exploring other precursors to further enhance electrode performance.

1. Introduction

Supercapacitors, renowned for their exceptional power density and rapid charge-discharge capabilities, are indispensable components in modern energy storage systems. Sustainable activated carbons, characterized by their extensive surface area and porous structure, are emerging as promising electrode materials for these devices [1][2].

Michelia Champaca, a hardwood species commonly found in Nepal, possesses a dense structure and high lignin content, making it an ideal candidate for producing high-performance activated carbon [3]. The dense structure and high lignin content of hardwood offer a rich source of carbon. Upon activation, this carbon develops exceptional porosity and surface area, both of which are crucial for energy storage applications.

This study explores the production of activated carbon from *Michelia Champaca* wood using two distinct carbonization methods: **Single-Step Carbonization (SSC)** and **Double-Step Carbonization (DSC)**. In the SSC method, wood powder mixed with phosphoric acid is directly carbonized at the target temperature for three hours, achieving simultaneous carbonization and activation. This approach encourages the formation of a highly porous structure and large surface area, leveraging the high lignin content to create a rigid carbon matrix suitable for achieving superior energy and power densities in supercapacitors [4], [5],[6].

The DSC method follows a two-step strategy: the wood powder is initially carbonized at 400°C for one hour, followed by overnight impregnation with phosphoric acid. The impregnated material is subsequently carbonized again at 400°C for an additional hour. This method aims to achieve more controlled activation and tailored pore characteristics, offering a more energy-efficient alternative by

reducing continuous high-temperature heating. The DSC process saves one hour of carbonization time and decreases energy consumption, making it a potentially sustainable option.

The objectives of this research are:

- To prepare activated carbon electrodes from *Michelia Champaca* wood waste using SSC and DSC at various temperatures.
- To characterize the physical and chemical properties of the prepared electrodes.
- To evaluate the electrochemical performance of the activated carbon electrodes in supercapacitor applications.
- To assess the energy efficiency of the carbonization processes.
- To compare the performance of activated carbon electrodes produced by SSC and DSC to determine the optimal carbonization method for supercapacitor applications.

Previous studies have shown that SSC often produces activated carbons with superior electrochemical properties due to the synergistic effect of simultaneous carbonization and activation [4],[7]. However, the influence of carbonization temperature on electrode performance remains to be explored. By addressing these objectives, this research contributes to the development of sustainable and high-performance energy storage materials while optimizing the production process.

2. Materials and Methods

2.1 Materials

Wood waste was collected from local joinery shops in Kathmandu, Nepal, for this study. An analytical-grade activating agent, 85% H_3PO_4 with a specific gravity of 1.73 g/ml (15.0 M), was obtained from Fischer Scientific, India (P) Ltd. Additional chemicals used included carbon black, polyvinylidene fluoride (PVDF), and N-methyl pyrrolidine (NMP), sourced from Sigma-Aldrich (USA) and APS Ajax Finechem (Australia).

The Ni-foam substrate employed in the experiments was procured from PRED MATERIALS International (USA). Ni foam is a popular choice for current collectors and substrates in electrochemical energy storage devices due to its unique properties. Its three-dimensional porous structure, combined with its lightweight nature, provides a large surface area for active material deposition [8],[9],[10]. Moreover, Ni foam's excellent electrical conductivity ensures efficient current collection and distribution, making it an ideal substrate for supporting high-performance active materials in supercapacitors and other energy storage applications.

2.2 Methods:

Synthesis of Activated Carbons

To synthesize activated carbons, sun-dried wood waste was finely ground and sieved to a particle size of 100 μm . A total of 80 grams of this powder was mixed with an equal volume of 85% H_3PO_4 and allowed to soak at 25°C for 24 hours. This 1:1 ratio was selected based on previous research findings [11], [12] that indicated its effectiveness in producing optimal results. The mixture was subsequently heated to 110°C for 2 hours, following established synthesis protocols.

Carbonization Methods

To optimize the electrochemical properties of the activated carbon for supercapacitor applications, two distinct carbonization methods were employed:

1. **Single-Step Carbonization (SSC):** The wood powder mixed with phosphoric acid was directly carbonized at 400°C and 500°C separately for 3 continuous hours in an inert atmosphere of N_2 . This one-step approach aims to achieve simultaneous carbonization and activation, potentially leading to a more developed pore structure and enhanced surface area [3], [12].
2. **Double-Step Carbonization (DSC):** The wood powder was initially carbonized at 400°C for 1 hour, followed by overnight phosphoric acid impregnation. Subsequently, the impregnated material was carbonized again at 400°C for another hour, allowing for controlled activation and tailored pore characteristics.

Post-Treatment

After carbonization, each sample was air-cooled and washed with hot distilled water until a neutral pH was achieved. Once completely dried, the samples were finely powdered again, resulting in three distinct activated carbons: SSC-400°C, SSC-500°C and DSC-400°C.

2.3. Instrumentation

Thermogravimetric analysis (TGA) of raw wood powder was performed using a SDT Q600 Version 20.9, Build 20 thermogravimetric analyzer (USA).

Characterization of activated carbons (SSC-400°C, SSC-500°C and DSC-400°C):

- Phase state: X-ray diffractometer (RIGAKU, Japan)
- Defect analysis: Raman spectrometer (labRAM HR800, France; JOBIN YVON, Finland)
- Oxygen content: Fourier transform infrared spectroscopy (FTIR) (BRUKER-OPTIK GMBH, Germany; Vertex 70/80, USA)
- Surface area and pore volume: Brunauer-Emmett-Teller (BET) method (Micromeritics ASAP 2020 system, USA)
- Surface morphology: Scanning electron microscopy (SEM) (Mini SEM nanoeyes, Korea)
- Porous structure: Transmission electron microscopy (TEM) (JEOL JEM 2100) for deeper analysis, complementing SEM insights

2.4. Assembly of Electrodes

Three different electrodes were fabricated using a blend of:

- 8 mg of each activated carbon (AC) powder (individually for each electrode)
- 1 mg of carbon black powder
- 1 mg of polyvinylidene fluoride (PVDF) powder

Maintaining an 8:1:1 ratio (AC:carbon black:PVDF), this mixture was dispersed in 200 mL of N-methyl-2-pyrrolidone (NMP) solution to form a uniform electrode slurry. The slurry was then applied onto a 1 cm² area of three separate rectangular Ni-foam electrode substrates. After drying overnight in a 70°C oven, these standardized electrodes were ready for electrochemical testing.

[10],[11], [12].

Before further testing, all the three electrodes, were immersed in a 6M KOH aqueous electrolyte solution overnight. This crucial step aimed to remove any contaminants and activate the electrode surfaces, ensuring reliable and accurate electrochemical performance [3],[4],[6].

2.5. Electrochemical Characterizations

The performances of the three as-fabricated electrodes (SSC-400°C, SSC-500°C and DSC-400°C electrodes), electrodes were evaluated individually using a three-electrode setup in a 6M KOH aqueous solution. Pt plates and Ag/AgCl served as counter and reference electrodes, respectively. All experiments were conducted at room temperature using a 'Metrohm Autolab (PGSTAT 302 N) potentiostat/galvanostat' system [4],[5],[6].

Cyclic voltammetry (CV) analysis provided insights into the redox behavior and charge storage potential of the electrodes. Measurements were conducted within a potential window of -1.0 to -0.2 V at various scan rates of 2, 5, 10, 20, 50, and 100 mV s⁻¹ (However, only CV at 100 mV s⁻¹ has been shown for clarity) [4],[5],[6].

Galvanostatic charge-discharge (GCD) tests assessed the electrodes' charge/discharge performance at different current densities of 1, 2, 3, 5, 10, 15, and 20 Ag⁻¹ (only at 1 Ag⁻¹ has been shown for clarity). Cyclic stability (% retention) was estimated based on data from these tests [11],[12].

Electrochemical impedance spectroscopy (EIS) data, acquired using a 10 mV perturbation signal across a frequency range of 100 kHz to 0.1 Hz, provided insights into the impedance characteristics of the electrodes and the resistance within the system [12],[13]. The data was analyzed using the Nova 1.11 program.

3. Results and Discussion

3.1. Thermal Decomposition of *Michelia Champaca* Wood Powder

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were employed to investigate the thermal decomposition behavior of raw *Michelia Champaca* wood powder. TGA measures mass loss during heating, while DSC monitors heat (enthalpy) flow into or out of the sample. Figure 1 presents the TGA/DSC plot of raw wood powder.

Key Observations

Mass Loss:

- **Initial weight loss (0–200°C):** Primarily attributed to the evaporation of moisture and volatile compounds.
- **Major weight loss (200–400°C):** Indicates the decomposition of cellulose, hemicellulose, and lignin, accompanied by significant exothermic reactions. The peak at approximately 391.3°C corresponds to the most intense decomposition.
- **Residual mass (400–800°C):** Consists primarily of inorganic ash [12], [14].
- **Enthalpy Flow:**
 1. **Exothermic peaks:** Correspond to the decomposition of various wood components, with the most prominent peak at 391.3°C, likely associated with cellulose and hemicellulose degradation.
 2. **Endothermic peaks:** May be present at lower temperatures, indicating the absorption of heat during moisture evaporation.

Analysis and Conclusions:

- **Thermal stability:** The wood powder exhibits moderate thermal stability, with most mass loss occurring between 200 and 400°C.
- **Decomposition mechanism:** Multiple exothermic peaks suggest a complex decomposition process involving the breakdown of different wood components.
- **Composition:** The presence of inorganic minerals is indicated by the residual mass.
- **Energy content:** The exothermic peaks suggest a significant heat content, making the wood powder a potential source of energy [15].

Carbonization Temperature Selection:

The TGA/DSC results indicate that the precursor material becomes more stable beyond 400°C. This suggests that 400°C is a suitable temperature for the carbonization process in this study, as it minimizes further mass loss and decomposition while ensuring the removal of volatile components [12].

3.2. Structural analysis of activated carbon

3.2.1. XRD and Raman analysis:

Figure 2 (**a and b**) shows the XRD and Raman spectra of the three activated carbon samples: SSC-400°C, SSC-500°C, and DSC-400°C respectively. These analyses provide insights into the structural properties and potential electrochemical performance of the materials.

XRD Analysis

Figure 2a presents the XRD patterns of the as-prepared *Michelia Champaca*-derived activated carbon. All three samples exhibit broad peaks around $2\theta = 25^\circ$, indicative of a predominantly amorphous structure, consistent with the expected characteristics of activated carbon. Additionally, a small, broad peak around $2\theta = 25^\circ$ is likely associated with the (002) plane of graphitic carbon, suggesting the presence of small, disordered graphitic-like domains within the samples.

Raman Analysis

The Raman spectra of the samples show clear D and G bands, confirming their carbon nature. The D band is directly associated with defects and disorder in the carbon structure, while the **G band** represents the graphitic structure. Therefore, the ratio of ID/IG provides a direct measure of structural disorder [16][17].

The calculated ID/IG ratios for SSC-400°C, SSC-500°C, and DSC-400°C are 0.9, 1.3, and 1.9, respectively. These values are consistent with the amorphous nature observed in the XRD patterns, as a higher ID/IG ratio generally indicates a more disordered structure (Fig. 2b).

Electrochemical Implications

The amorphous nature of SSC-400°C, as evidenced by its lower ID/IG ratio, suggests a larger surface area and more accessible pores, which can enhance its electrochemical performance for supercapacitor applications. These features can improve ion diffusion and charge transfer, leading to higher specific capacitance and better rate capability.

Summary: XRD and Raman analysis

The XRD and Raman analyses indicate that SSC-400°C exhibits a more amorphous structure compared to SSC-500°C and DSC-400°C. This amorphous nature, as evidenced by the lower ID/IG ratio in the Raman spectra, suggests that SSC-400°C may have favorable properties for supercapacitor applications, such as a larger surface area and more accessible pores.

However, further characterization is necessary to confirm the relationship between the amorphous structure and electrochemical performance. Techniques like BET surface area analysis and pore size distribution measurements can provide more quantitative information about the material's surface properties and porosity, which are crucial factors for energy storage applications.

3.2.2. FTIR Analysis of Activated Carbon Samples

Fourier-Transform Infrared Spectroscopy (FTIR) was employed to identify functional groups present in the activated carbon samples. Figure 3 presents the FTIR spectra of the samples, along with peak assignments and corresponding functional groups.

Peak Assignments and Functional Groups

- **3291 cm⁻¹**: O-H stretching (hydroxyl groups)
- **1585 cm⁻¹**: C = C stretching (aromatic rings or double bonds)
- **1186 cm⁻¹**: C-O stretching (ether or ester groups)
- **660 cm⁻¹**: C-H bending (aliphatic or aromatic hydrocarbons)
- **2344 cm⁻¹**: CO absorption

Analysis of Oxygen-Containing Functional Groups

- **SSC-400°C**: Exhibits prominent peaks at 3291 cm⁻¹ and 1186 cm⁻¹, indicating the significant amount of hydroxyl and ether/ester functional groups [18].
- **SSC-500°C**: Shows less intense peaks associated with hydroxyl and ether/ester groups compared to SSC-400°C, suggesting a decrease in their concentration of these functional groups.
- **DSC-400°C**: Has almost no peaks related to hydroxyl and ether/ester groups, indicating a very low or negligible concentration.

Importance of Oxygen-Containing Functional Groups in Electrochemical Performance

Oxygen-containing functional groups, such as hydroxyl and ether/ester groups, play a crucial role in the electrochemical performance of activated carbon materials, particularly in supercapacitors:

Enhanced Wettability

These functional groups can improve the wettability of the carbon material by interacting with electrolyte molecules, leading to better ion transport and charge storage.

Pseudocapacitance

Oxygen-containing functional groups can contribute to pseudocapacitance, a mechanism where charge is stored through faradaic reactions involving the functional groups. This can increase the overall capacitance of the material [19],[20].

Summary: FTIR Analysis of Activated Carbon Samples

The FTIR analysis reveals that SSC-400°C contains a higher concentration of oxygen-containing functional groups compared to SSC-500°C and DSC-400°C. The presence of these functional groups can

positively influence the electrochemical performance of activated carbon materials by enhancing wettability, contributing to pseudocapacitance, and improving overall electrochemical activity.

3.3. BET Plot Analysis

The BET plot illustrates the adsorption and desorption isotherms of nitrogen gas on activated carbon samples prepared under different conditions (SSC-400°C, SSC-500°C, and DSC-400°C). The adsorption isotherms represent the amount of nitrogen gas adsorbed at various relative pressures (P/P°), while the desorption isotherms represent the amount of nitrogen gas desorbed as the pressure is reduced. Figure 4 presents the BET plot for the activated carbon samples.

Key Observations

- 1. **Type I Isotherms:** All samples exhibit a Type I isotherm, characteristic of microporous materials. This indicates that the majority of pores in these activated carbons are smaller than 2 nm [21].
- 2. **Hysteresis Loops:** Hysteresis loops are observed between the adsorption and desorption branches for all samples, suggesting the presence of mesopores (pore size between 2 and 50 nm). The shape and size of the hysteresis loops can provide information about the pore size distribution and connectivity.
- 3. **Adsorption Capacity:** The total amount of nitrogen adsorbed at $P/P^\circ = 1$ (saturation) can be used to estimate the specific surface area of the samples.

Table 1: BET Analysis of Activated Carbon Samples

Activated carbons	Specific Surface Area (m ² g ⁻¹)	Pore size (BJH Ads) (nm)	Pore Volume (BJH Ads) (cm ³ g ⁻¹)
SSC-400°C	1894.3	5.4	2.7
SSC-500°C	1390.4	4.1	1.8
DSC-400°C	969.2	1.9	0.9

Interpreting the Differences

Based on the provided table, we can make the following observations:

- **SSC-400°C:**
 - Highest specific surface area (1894.3 m²/g), indicating the largest number of active sites for charge storage.
 - Largest pore volume (2.7 cm³/g) and broader pore size distribution (5.4 nm), suggesting better ion transport and rate capability.

- **SSC-500°C:**
 - Lower specific surface area ($1390.4 \text{ m}^2/\text{g}$) compared to SSC-400°C.
 - Smaller pore volume ($1.8 \text{ cm}^3/\text{g}$) and narrower pore size distribution (4.1 nm), indicating fewer mesopores and potentially limiting ion transport.
- **DSC-400°C:**
 - Lowest specific surface area ($969.2 \text{ m}^2/\text{g}$) among the samples.
 - Smallest pore volume ($0.9 \text{ cm}^3/\text{g}$) and narrowest pore size distribution (1.9 nm), suggesting the least amount of mesoporosity and potentially limiting ion transport.

Implications for Electrochemical Performance

- **Capacitance:** A larger specific surface area (SSC-400°C) generally correlates with higher capacitance due to the increased number of active sites for charge storage[12],[22].
- **Rate Capability:** A broader pore size distribution (SSC-400°C) can facilitate ion diffusion, leading to better rate performance. A narrower pore size distribution (DSC-400°C) may limit ion transport, especially at higher current densities.
- **Energy Density:** While a wider pore size distribution can enhance rate capability, it may also lead to lower energy density. A narrower pore size distribution (DSC-400°C) can potentially improve energy density by allowing for more efficient packing of ions within the pores [23].

Summary: BET Plot Analysis

The BET analysis reveals that all samples are primarily microporous, with varying degrees of mesoporosity. SSC-400°C demonstrates the highest specific surface area, pore volume, and a wider pore size distribution, making it more suitable for supercapacitor applications requiring both high capacitance and good rate capability. In contrast, DSC-400°C has a smaller surface area and narrower pore distribution, which might benefit applications prioritizing energy density.

3.4. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) provides high-resolution images of the surface morphology of materials, making it particularly useful for visualizing the microstructure and surface features of solids.

Interpretation of the SEM Images

Based on the provided SEM images, we can make the following observations:

- **SSC-400°C:** The image shows a relatively rough and porous surface with a heterogeneous structure. Visible pores and cracks suggest a well-developed pore structure.

- **SSC-500°C:** The surface appears smoother and less porous compared to SSC-400°C. The pores seem smaller and less interconnected.
- **DSC-400°C:** This sample exhibits a very smooth surface with minimal porosity. The particles appear more compact and uniform in size.

Correlating with Previous Analysis

The SEM images are consistent with the findings from the BET and FTIR analyses:

- **SSC-400°C:** The rough and porous surface observed in the SEM image aligns with the higher surface area and wider pore size distribution indicated by the BET analysis. The presence of oxygen-containing functional groups, as suggested by the FTIR analysis, might contribute to the surface roughness and porosity[12], [24].
- **SSC-500°C:** The smoother surface and smaller pores observed in the SEM image are consistent with the lower surface area and narrower pore size distribution found in the BET analysis. The decrease in oxygen-containing functional groups might also contribute to the smoother surface.
- **DSC-400°C:** The very smooth surface and minimal porosity observed in the SEM image are consistent with the low surface area and narrow pore size distribution indicated by the BET analysis. The absence of oxygen-containing functional groups might further contribute to the compact and uniform structure.

Implications for Electrochemical Performance

The surface morphology observed in the SEM images can significantly influence the electrochemical performance of the activated carbon materials:

- **Porosity:** A porous surface can provide more active sites for charge storage, leading to higher capacitance. However, excessive porosity might also lead to increased diffusion resistance.
- **Surface Roughness:** A rough surface can enhance the wettability of the material, improving the interaction with the electrolyte.
- **Particle Size and Distribution:** A uniform particle size distribution can facilitate ion transport and improve the rate capability of the material [25].

Summary: Scanning Electron Microscopy (SEM)

The SEM images provide valuable insights into the surface morphology of the activated carbon samples. The observations are consistent with the findings from the BET and FTIR analyses, suggesting a correlation between the surface structure and the electrochemical properties of these materials. By considering the factors mentioned above, a more comprehensive understanding of the relationship between surface morphology and electrochemical performance can be obtained.

3.5. Transmission Electron Microscopy (TEM) analyses:

Transmission Electron Microscopy (TEM) provides high-resolution images of the internal structure of materials, revealing important characteristics such as particle size, shape, and distribution.

Interpretation of the TEM Images

Based on the provided TEM images, we can make the following observations:

- **SSC-400°C:** The image shows a relatively agglomerated structure with particles of varying sizes. Some larger particles are visible, along with smaller, more dispersed nanoparticles.
- **SSC-500°C:** The particles appear to be slightly smaller and more uniformly distributed compared to SSC-400°C. The agglomeration is reduced, and the nanoparticles are more dispersed.
- **DSC-400°C:** This sample exhibits a more uniform distribution of nanoparticles with a smaller average size compared to the other two samples. The particles are well-dispersed with minimal agglomeration.

Correlating with Previous Analysis

The TEM images align well with the findings from the SEM and BET analyses:

- **SSC-400°C:** The agglomerated structure observed in the TEM image corresponds with the rough and porous surface seen in the SEM image, indicating larger particle size and potential for agglomeration [26].
- **SSC-500°C:** The smaller and more dispersed nanoparticles in the TEM image are consistent with the smoother surface and narrower pore size distribution observed in the SEM and BET analyses.
- **DSC-400°C:** The uniform distribution of smaller nanoparticles in the TEM image matches the compact and uniform structure seen in the SEM image and the low surface area and narrow pore size distribution indicated by the BET analysis.

Implications for Electrochemical Performance

The particle size and distribution observed in the TEM images can significantly influence the electrochemical performance of the materials:

- **Particle Size:** Smaller Particle Sizes: These can provide a larger surface area for charge storage, leading to higher capacitance. This is beneficial for applications requiring high energy density.
- **Agglomeration:** Excessive agglomeration can hinder ion transport and reduce the effective surface area, negatively impacting the material's performance.
- **Particle Distribution:** Uniform Distribution: A uniform distribution of nanoparticles can facilitate ion diffusion, improving the rate capability of the material. This ensures better performance in applications requiring rapid charge and discharge cycles [27].

Summary: Transmission Electron Microscopy (TEM) analyses

The TEM images provide valuable insights into the microstructure of the nanoparticle samples. The observations are consistent with the findings from the SEM and BET analyses, suggesting a strong correlation between the particle size, distribution, and the electrochemical properties of these materials.

This information is crucial for optimizing the materials for specific electrochemical applications, such as batteries or supercapacitors.

A comprehensive structural analysis of the activated carbon samples using XRD, Raman spectroscopy, and FTIR, BET, revealed that **SSC-400°C** possesses an optimal pore structure and surface area, significantly outperforming the other synthesized materials. While SSC-500°C exhibited comparable characteristics, higher calcination temperatures led to a deterioration in performance due to pore collapse and structural modifications. DSC-400, on the other hand, demonstrated inferior surface area and unsatisfactory results in scanning electron microscopy (SEM), transmission electron microscopy (TEM), XRD, Raman, and FTIR analyses. These findings strongly suggest that SSC-400°C has the potential for exceptional electrochemical behavior, particularly in energy storage applications such as supercapacitors. To further explore its electrochemical performance, cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS) were employed.

4. Electrochemical Performances of activated carbon electrodes

4.1. Cyclic voltammetry (CV)

Cyclic voltammetry (CV) analysis provided insights into the redox behavior and charge storage potential of the electrodes. To determine the optimal potential window, CV curves of the electrodes were investigated at different potential windows, i.e. (-1.2 to 0 V), (-1 to -0 V) and (-1.0 to -0.2 V) (Fig. not shown), using current density (A g⁻¹) versus potential (V vs Ag/AgCl). Among the three potential windows, the potential window of (-1.0 to -0.2 V) was found to be the best, exhibiting excellent EDLC behavior.

- **Capacitive Behavior:** The quasi-rectangular shape of the CV curves confirms the capacitive nature of the activated carbon materials [12], [28].
- **Current Response:** The current response increases with increasing potential, indicating a linear relationship between current and potential, which is typical of capacitive behavior.
- **SSC-400°C:** This sample shows the highest current response, suggesting the highest capacitance.
- **DSC-400°C:** This sample shows the lowest current response, indicating the lowest capacitance.
- **SSC-500°C:** The current response of SSC-500°C falls between SSC-400°C and DSC-400°C.

Additional Observations

- **Scan Rate:** CV curves were obtained at multiple scan rates (2, 5, 10, 50, and 100 mV/s). Only the 100 mV/s curves are shown for clarity. Analyzing the CV curves at different scan rates can provide insights into the rate capability of the materials [4].

Correlating with Previous Characterizations

The CV results can be correlated with the findings from the BET, FTIR, and SEM analyses:

- **High Surface Area:** The higher capacitance of SSC-400°C is likely due to its larger surface area, as indicated by the BET analysis.
- **Pore Structure:** The pore structure of the materials can also influence the capacitance. A wider pore size distribution can facilitate ion transport, leading to higher capacitance.
- **Functional Groups:** The presence of oxygen-containing functional groups can contribute to pseudocapacitance, enhancing the overall capacitance.
- **Particle Size and Distribution:** The surface morphology and particle size distribution observed in the SEM images can also affect the electrochemical performance.

Implications for Electrochemical Performance

The CV analysis provides insights into the electrochemical behavior of the activated carbon samples. The higher capacitance of SSC-400°C suggests its potential for supercapacitor applications. The lower capacitance of DSC-400°C might be attributed to its smaller surface area and narrower pore size distribution [29].

Summary: Cyclic Voltammetry (CV) Analysis

The cyclic voltammetry analysis revealed the capacitive nature of the activated carbon materials. The current response of the electrodes increased with increasing potential, indicating a linear relationship between current and potential, which is characteristic of capacitive behavior. Among the samples, SSC-400°C exhibited the highest capacitance, likely due to its larger surface area and favorable pore structure. The CV results suggest that SSC-400°C is a promising candidate for supercapacitor applications.

4.2. Galvanostatic Charge-Discharge (GCD) analysis

The GCD plot shows the potential response of the activated carbon samples (SSC-400°C, SSC-500°C, and DSC-400°C) as a function of time during constant current charging and discharging. The x-axis represents time (s), and the y-axis represents the potential (V vs Ag/AgCl). Though various current densities of 1, 2, 5, 10, and 20 A g⁻¹ were used, the GCD plot at 1 A g⁻¹ is shown here for clarity, as showing all current densities would make the plot too compact and unclear.

Specific Capacitance Calculation

The specific capacitance (C_s) was calculated using the following equation derived from the GCD curves:

$$C_s = \frac{I \Delta t}{m \Delta V} \dots\dots\dots(1)$$

Where,

- C_s (F g⁻¹) is the specific capacitance
- I (A) is the discharge current
- t (s) is the discharge time
- m (g) is the mass of the active electrode material
- ΔV (V) is the potential window

Specific Capacitance Results

Using this equation, the specific capacitance values for the activated carbon electrodes were found to be 292.2 F/g for SSC-400°C, 157.1 F/g for SSC-500°C, and 74.3 F/g for DSC-400°C.

Rate Capability Evaluation

To further evaluate the rate capability of the activated carbon samples, we analyzed the variation of specific capacitance with current density. The resulting plot is shown in Fig. 8.

Key Observations

- **Specific Capacitance Trends:** SSC-400°C exhibits the highest specific capacitance across the entire current density range, followed by SSC-500°C and DSC-400°C.
- **Capacitance Decay:** All three samples show a decrease in specific capacitance with increasing current density, indicating diffusion limitations and ohmic losses.

Correlations and Implications

The higher specific capacitance of SSC-400°C can be attributed to its larger surface area, as indicated by the BET analysis. Additionally, the wider pore size distribution in SSC-400°C facilitates ion transport, leading to better rate capability and potentially higher specific capacitance at higher current densities. The presence of oxygen-containing functional groups in the activated carbons can also contribute to the overall capacitance [4],[12], [30].

The GCD analysis demonstrates the rate capability of the activated carbon samples. SSC-400°C exhibits the best rate capability, maintaining a high specific capacitance even at higher current densities. This suggests its potential for applications requiring rapid charge and discharge, such as pulsed power devices or energy storage systems in electric vehicles.

Implications for Electrochemical Performance

The GCD analysis provides insights into the specific capacitance and rate capability of the activated carbon samples. The higher specific capacitance of SSC-400°C suggests its potential for supercapacitor applications in energy storage devices. The higher internal resistance of DSC-400°C might limit its performance at high current densities, making it less suitable for applications requiring rapid charge and discharge.

Summary: Galvanostatic Charge-Discharge (GCD) analysis

The galvanostatic charge-discharge (GCD) analysis evaluated the specific capacitance and rate capability of the activated carbon electrodes. SSC-400°C exhibited the highest specific capacitance (292.2 F/g) and the best rate capability, maintaining a high specific capacitance even at higher current densities. DSC-400°C showed the lowest specific capacitance (74.3 F/g) and exhibited a significant decrease in capacitance at higher current densities. The results suggest that SSC-400°C is a promising candidate for supercapacitor applications, particularly those requiring high power density. The observed trends can be correlated with the structural and morphological properties of the materials, as revealed by the BET, FTIR, SEM, and CV analyses.

Percentage capacity retention

Key Observations

- **Capacity Fade:** All three samples exhibit a gradual decrease in capacity retention with increasing cycle number, indicating capacity fading.
- **SSC-400°C:** This sample shows the best capacity retention, retaining around 96.2% of its initial capacity after 1000 cycles.
- **DSC-400°C:** This sample shows the worst capacity retention, retaining only 66.4% of its initial capacity after 1000 cycles.
- **SSC-500°C:** The capacity retention of SSC-500°C falls between SSC-400°C and DSC-400°C.

Correlating with Previous Characterizations

The capacity retention can be correlated with the findings from the BET, FTIR, SEM, CV, and GCD analyses:

- **Surface Area and Pore Structure:** A larger surface area and a wider pore size distribution can contribute to better capacity retention by providing more active sites for charge storage and facilitating ion transport.
- **Functional Groups:** The presence of oxygen-containing functional groups can influence the stability of the electrode material and affect capacity retention.
- **Particle Size and Distribution:** The surface morphology and particle size distribution can also impact the long-term stability of the material.

Implications for Electrochemical Performance

The capacity retention curves provide insights into the cycling stability of the activated carbon samples. The higher capacity retention of SSC-400°C suggests its superior long-term performance. The lower capacity retention of DSC-400°C might be attributed to its smaller surface area, narrower pore size distribution, or the presence of less stable functional groups [4],[12],[29]

Summary: Percentage Capacity Retention

The cycling stability of the activated carbon samples was evaluated using percentage capacity retention. SSC-400°C exhibited the best capacity retention, retaining around 96.2% of its initial capacity after 1000 cycles. DSC-400°C showed the worst capacity retention, retaining only 66.4% of its initial capacity. The capacity retention can be correlated with the surface area, pore structure, functional groups, and particle size distribution of the samples. These factors influence the long-term stability of the electrode material and its ability to maintain high capacitance over repeated cycles.

4.3. Electrochemical Impedance Spectroscopy (EIS) Analysis of Activated Carbon Electrodes

Electrochemical impedance spectroscopy (EIS) is a powerful technique used to investigate the electrochemical behavior of materials. By applying a small amplitude AC signal to an electrochemical system and measuring the resulting impedance response, EIS can provide valuable insights into charge transfer kinetics, diffusional limitations, and interfacial processes.

Nyquist Plot Analysis

The provided Nyquist plot shows the impedance response of the activated carbon samples (SSC-400°C, SSC-500°C, and DSC-400°C) in a frequency range from 100 mHz to 100 kHz. The x-axis represents the real part of the impedance (Z'), and the y-axis represents the negative imaginary part of the impedance ($-Z''$).

Key Observations

- **Semicircle in the high-frequency region:** This represents the charge transfer resistance (**R_{ct}**). A smaller semicircle indicates a lower R_{ct}, which is desirable for better electrochemical performance.
- **Sloping line in the low-frequency region:** This represents the Warburg impedance (**Z_w**), associated with diffusional limitations. A steeper slope suggests lower diffusional resistance.

Quantitative Analysis:

To quantify the R_{ct} and Z_w values, the Nyquist plot can be fitted to an equivalent circuit model, such as the Randles circuit. This model consists of a resistor (R_s) representing the electrolyte resistance, a capacitor (C_{dl}) representing the double-layer capacitance, a resistor (R_{ct}) representing the charge transfer resistance, and a Warburg element (Z_w) representing diffusional limitations [25], [29].

By fitting the Nyquist plot to the Randles circuit, the values of R_{ct} and Z_w can be extracted. The following Table 2 summarizes the extracted values for the three samples:

Table 2: Extracted charge transfer resistance (R_{ct}) and Warburg impedance (diffusional resistance) (Z_w) values from Nyquist plot fitting for activated carbon electrodes

Electrodes	R_{ct} (Ω)	Z_w (Ω)
SSC-400°C	4.4	6.3
SSC-500°C	6.3	7.2
DSC-400°C	7.2	8.1

Interpretation:

- **R_{ct} :** SSC-400°C exhibits the lowest R_{ct} , indicating the fastest charge transfer kinetics. DSC-400°C shows the highest R_{ct} , suggesting slower charge transfer.
- **Z_w :** SSC-400°C also has the lowest Z_w , implying the least diffusional limitations. DSC-400°C exhibits the highest Z_w , indicating significant diffusional resistance.
- **Overall impedance:** SSC-400°C demonstrates the lowest overall impedance, combining the benefits of low R_{ct} and Z_w . This suggests superior electrochemical performance [4], [12].

Correlation with Previous Characterizations

The EIS results can be correlated with the findings from other characterization techniques, such as BET, FTIR, SEM, CV, and GCD. For example:

- **High surface area:** A larger surface area can lead to lower R_{ct} .
- **Pore structure:** A wider pore size distribution can facilitate ion transport, reducing diffusional resistance.
- **Functional groups:** The presence of oxygen-containing functional groups can influence the charge transfer kinetics and R_{ct} .
- **Particle size and distribution:** The surface morphology and particle size distribution can also impact the electrochemical properties.

Summary: Electrochemical Impedance Spectroscopy Analysis

The electrochemical impedance spectroscopy (EIS) analysis revealed the charge transfer kinetics and diffusional limitations of the activated carbon electrodes. SSC-400°C exhibited the lowest charge

transfer resistance (Rct) and diffusional resistance (Zw), indicating the fastest charge transfer kinetics and least diffusional limitations. These favorable properties suggest that SSC-400°C is a promising candidate for supercapacitor applications requiring high power density and good rate capability

4.4. Power and Energy density

Analyzing the Ragone Plot for Activated Carbon Supercapacitors

The Ragone plot is a powerful visualization tool that illustrates the relationship between energy density and power density for energy storage devices. By plotting these two parameters against each other, the Ragone plot provides a clear comparison of different materials and technologies.

In this case, the Ragone plot shows the performance of three activated carbon samples (SSC-400°C, SSC-500°C, and DSC-400°C) as supercapacitors. The x-axis represents the energy density, which is the amount of energy stored per unit mass, while the y-axis represents the power density, which is the rate at which energy can be delivered.

Key Observations:

- **Position of Samples:** SSC-400°C is positioned towards the top-right corner of the plot, indicating a high energy density and high power density. DSC-400°C is positioned towards the bottom-left corner, indicating a low energy density and low power density. SSC-500°C falls somewhere in between.
- **Trade-off Between Energy and Power Density:** There is a general trade-off between energy density and power density. Materials with high energy density tend to have lower power density, and vice versa [30].

Quantitative Analysis (Power and energy density evaluation):

To obtain quantitative values for energy and power density, the following equations were used:

$$ED = \frac{1}{8} C \Delta v^2 \dots\dots\dots (3)$$

$$PD = \frac{E}{\Delta t} \dots\dots\dots (4)$$

In the equations for energy density and power density, the following variables are used:

- V: Potential window (voltage range)
- t: Discharge time (seconds)
- E: Energy density (Wh/kg)
- P: Power density (W/kg)
- Csp: Specific capacitance (F/g)

It's important to note that in this study, the energy density is calculated by dividing the specific capacitance by 8. This is due to the use of a three-electrode system for measuring the electrochemical performance. In a three-electrode system, the reference electrode effectively doubles the total capacitance, leading to the factor of 8 in the energy density calculation [4],[12].

Explanation for Division by 8 in Three-Electrode Systems:

The factor of 8 in the energy density equation arises from the specific configuration of the three-electrode system used in this study. In a three-electrode system, the working electrode is measured against a reference electrode, while the counter electrode balances the current. This configuration effectively doubles the total capacitance of the system compared to a two-electrode system [22].

Since energy density is proportional to the square of the capacitance, dividing by 8 instead of 2 accounts for this doubled capacitance and provides an accurate representation of the energy stored in the working electrode.

Correlation with Characterizations:

The Ragone plot can be correlated with the findings from other characterization techniques, such as BET, FTIR, SEM, CV, GCD, and EIS. For example:

- **High surface area:** A larger surface area can contribute to higher energy and power density.
- **Pore structure:** The pore structure can influence both energy and power density. A wider pore size distribution can facilitate ion transport and improve the rate capability, leading to higher power density.
- **Functional groups:** The presence of oxygen-containing functional groups can affect the electrochemical properties and influence the position of the samples on the Ragone plot.
- **Particle size and distribution:** The surface morphology and particle size distribution can also impact the energy and power density.

Implications for Electrochemical Performance:

The Ragone plot provides a visual representation of the overall electrochemical performance of the activated carbon samples. SSC-400°C exhibits the most desirable combination of energy density and power density, making it a promising candidate for supercapacitor applications. DSC-400°C, on the other hand, shows lower performance in terms of both energy and power density [22],[23].

Summary: Ragone Plot Analysis

The Ragone plot analysis revealed the energy density and power density of the activated carbon supercapacitors. SSC-400°C demonstrated the highest energy density and power density, positioning it towards the top-right corner of the plot. DSC-400°C exhibited the lowest energy density and power density, located towards the bottom-left corner. The Ragone plot highlights the trade-off between energy

density and power density, where materials with high energy density tend to have lower power density and vice versa. These findings suggest that SSC-400°C is a promising candidate for supercapacitor applications requiring a balance of energy and power performance.

5. Conclusion

Based on the comprehensive analysis of the activated carbon samples using various techniques (BET, FTIR, SEM, CV, GCD, EIS, and Ragone plot), the following key findings can be summarized:

Table.3: Electrochemical properties of the activated carbon samples, including specific capacitance, energy density, power density, charge transfer resistance (Rct), and Warburg impedance (diffusional resistance) (Zw)

Electrodes	Potential window(V)	Specific capacitance (Fg ⁻¹)	Energy density (Whkg ⁻¹)	Power density (Wkg ⁻¹)	Rct (Ω)	Zw (Ω)
SSC-400°C	-1 to -0.2	292.2	6.4	198.4	4.4	6.3
SSC-500°C	-1 to -0.2	157.1	3.5	195.3	6.3	7.2
DSC-400°C	-1 to -0.2	74.3	1.6	187.3	7.2	8.1

Electrochemical properties of the activated carbon samples, including specific capacitance, energy density, power density, charge transfer resistance (Rct), and Warburg impedance (diffusional resistance) (Zw)

As shown in Table 3, SSC-400°C exhibits superior electrochemical performance in all aspects:

- **Specific Capacitance:** SSC-400°C demonstrates the highest specific capacitance of 292.2 Fg⁻¹ indicating its ability to store a larger amount of charge per unit mass.
- **Energy Density:** The energy density of SSC-400°C is 6.4 Whkg⁻¹, which is significantly higher than the other samples. This suggests its potential for storing more energy per unit mass.
- **Power Density:** SSC-400°C also exhibits a high power density of 198.4 Wkg⁻¹, indicating its ability to deliver energy at a rapid rate.
- **Charge Transfer Resistance (Rct):** The Rct value of SSC-400°C is the lowest among the three samples, suggesting faster charge transfer kinetics.
- **Warburg Impedance (Zw):** SSC-400°C also has the lowest Zw value, indicating lower diffusional limitations within the electrode material.

In contrast, DSC-400°C demonstrates inferior electrochemical properties, with the lowest specific capacitance, energy density, and power density. This is likely due to its less favorable structural properties, as evidenced by the BET and SEM analyses.

SSC-500°C shows intermediate performance, with slightly lower specific capacitance and energy density compared to SSC-400°C. This may be attributed to some degradation of the material during the higher calcination temperature.

Overall, this study highlights the potential of activated carbon derived from sugarcane bagasse as a promising material for supercapacitor applications. Future research and development efforts could focus on optimizing the synthesis process to further enhance the performance of these materials and expand their applicability in various energy storage devices.

Declarations

Conflict of Interest

No potential conflicts of interest were reported.

Acknowledgements

The author gratefully acknowledges the Central Department of Chemistry at Tribhuvan University, Kirtipur, Nepal, and the Patan Multiple Campus, Institute of Science and Technology, Tribhuvan University, Patan Dhoka, Lalitpur, Nepal, for providing essential laboratory facilities to support this research.

Furthermore, the author extends sincere thanks to the Global Research Laboratory (GRL) at Sun Moon University, South Korea, and the Advanced Functional Material Physics (AMP) laboratory at Suranaree University of Technology (SUT), Thailand, for their invaluable contributions in conducting material characterization and electrochemical measurements, respectively.

Author Contribution

Dr. Dibyashree Shrestha conceived the research idea, designed and executed the experiments, analyzed the experimental data, interpreted the results, and drafted the manuscript. All aspects of the study were independently completed by the author.

References

1. Choi JH, Kim JE, Lim GH, Han J, Roh KC, Lee JW (2020) Comparison of the electrochemical properties of activated carbon prepared from woody biomass with different lignin content. *Wood Sci Techno* 54(5):1165–1180
2. Lin H, Liu Y, Chang Z, Yan S, Liu S, Han S (2020) A new method of synthesizing hemicellulose-derived porous activated carbon for high-performance supercapacitors. *Micropo Mesopo Mat* 292:109707
3. Taprial S (2015) A review on phytochemical and pharmacological properties of *Michelia champaca* Linn. Family: Magnoliaceae. *Int J Pharmacogn* 2:430–436

4. Shrestha D (2022a) Evaluation of Physical and Electrochemical Performances of Hardwood and Softwood derived Activated Carbon for Supercapacitor Application. *Mat Sci Ener Techno* 5:353–365
5. Shrestha D (2022b) Activated carbon and its hybrid composites with manganese (IV) oxide as effectual electrode materials for high performance supercapacitor. *Arab J Chem* 15(7):103946
6. Davide B, Toni V, Henrik R, Ulla L (2018) Comparison of the Properties of Activated Carbons Produced in One-Stage and Two-Stage Processes. *J Carbon Res MDPI* 4(3):41
7. Shrestha D (2021) Efficiency of wood-dust of *Dalbergia sisoo* as low-cost adsorbent for rhodamine-B dye removal. *Nanomaterials* 11(9):2217
8. Shrestha D (2024) Structural and electrochemical evaluation of renewable carbons and their composites on different carbonization temperatures for supercapacitor applications. *Heliyon* 10(4):e25628
9. Shrestha D (2023) Applications of functionalized porous carbon from bio-waste of *Alnus nepalensis* in energy storage devices and industrial wastewater treatment. *Heliyon* 9(4):e21804
10. Li X, Liu J, Chen J (2016) Ni-foam as a substrate for energy storage devices: A review. *J Mat Sci* 51(18):10431–10452
11. Shrestha D, Rajbhandari Nyachhyon A (2021) The Effects of Different Activating Agents on the Physical and Electrochemical Properties of Activated Carbon Electrodes Fabricated from Wood-dust of *Shorea robusta*. *Heliyon* 7:e07917
12. Shrestha D, Maensiri S, Wongpratut U, Lee SW, Rajbhandari Nyachhyon A (2019) *Shorea robusta* derived activated carbon decorated with manganese dioxide hybrid composite for improved capacitive behaviors. *J Environ Chem Engine* 7:103227
13. Shrestha D, Gyawali G, Rajbhandari A (2018) Preparation and Characterization of Activated Carbon from Waste Sawdust from Saw Mill. *J Sci Techno* 22(2):103–108
14. Levashov EA, Mukasyan AS, Rogachev AS, Shtansky DV (2017) Self-propagating high-temperature synthesis of advanced materials and coatings. *Int Mater Rev* 62(4):203–239
15. Nurazzi NM, Abdullah N, Norraahim MNF, Kamarudin SH, Ahmad S, Shazleen SS, Rayung M, Asyraf MRM, Kuzmin A (2022) Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) of PLA/cellulose composites. In *Poly(lactic acid)-based nanocellulose and cellulose composites* 145–164 CRC Press
16. Mehdi R, Naqvi SR, Khoja AH, Hussain R (2023) Biomass derived activated carbon by chemical surface modification as a source of clean energy for supercapacitor application. *Fuel* 348:128529
17. Xu L, Jia M, Li Y, Jin X, Zhang F (2017) High-performance MnO₂-deposited graphene/activated carbon film electrodes for flexible solid-state supercapacitor. *Sci Rep* 7(1):12857
18. Yaddanapudi HS, Tian K, Teng S, Tiwari A (2016) Facile preparation of nickel/carbonized wood nanocomposite for environmentally friendly supercapacitor electrodes. *Sci Rep* 6:33659
19. Kim JH, Kim SH, Kim BJ, Lee HM (2023) Effects of Oxygen-Containing Functional Groups on the Electrochemical Performance of Activated Carbon for EDLCs. *Nanomaterials* 13(2):262

20. Hwang KJ-H, Park SY, Lee JU, Kim GB, Kim H, Hong S (2019) Impact of the oxygen functional group of nitric acid-treated activated carbon on KOH activation reaction. *Carbon Lett* 29:281–287
21. Shrestha D (2022c) Nanocomposite electrode materials prepared from *Pinus roxburghii* and hematite for application in supercapacitors *J. Korean Wood Sci Techno* 50(4):219–236
22. Li YT, Pi YT, Lu LM, Xu SH, Ren TZ (2015) Hierarchical porous active carbon from fallen leaves by synergy of K₂CO₃ and their supercapacitor performance. *J Power Sources* 299:519–528
23. Zhang J, Yang H, Huang Z, Zhang H, Lu X, Yan J, Bo Z (2023) Pore-structure regulation and heteroatom doping of activated carbon for supercapacitors with excellent rate performance and power density. *Waste Dispos Sustainable Energy* 5(3):417–426
24. Goldstein JI, Newbury DE, Michael JR, Ritchie NW, Scott JHJ, Joy DC (2017) *Scanning electron microscopy and X-ray microanalysis*. Springer
25. Nazhipkyzy M, Yeleuov M, Sultakhan S, Maltay A, Zhaparova A, Assylkhanova D, Nemkayeva R (2022) Electrochemical Performance of Chemically Activated Carbons from Sawdust as Supercapacitor Electrodes. *Nanomaterials* 12:3391
26. Mast J, Verleysen E, Hodoroaba VD, Kaegi R (2020) Characterization of nanomaterials by transmission electron microscopy. *Measurement procedures*
27. Lv H, Pan Q, Song Y, Liu XX, Liu T (2020) A review on nano-/microstructured materials constructed by electrochemical technologies for supercapacitors. *Nano-Micro Lett* 12:1–56
28. Ahmad A, Gondal MA, Hassan M, Iqbal R, Ullah S, Alzahrani AS, Melhi S (2023) Preparation and characterization of physically activated carbon and its energetic application for all-solid-state supercapacitors: a case study. *ACS omega* 8(24):21653–21663
29. Wardani V, Rohmawati L, Setyarsih W, Alfarisi D, Subhan A (2019) Analysis of Charging/Discharging Supercapacitor Active Carbon/rGO Based on Natural Materials. *IOP Conf. Series: Journal of Physics: Conf. Series* 1491: 012044
30. Liu S, Wei L, Wang H (2020) Review on reliability of supercapacitors in energy storage applications. *Appl Energy* 278:115436

Figures

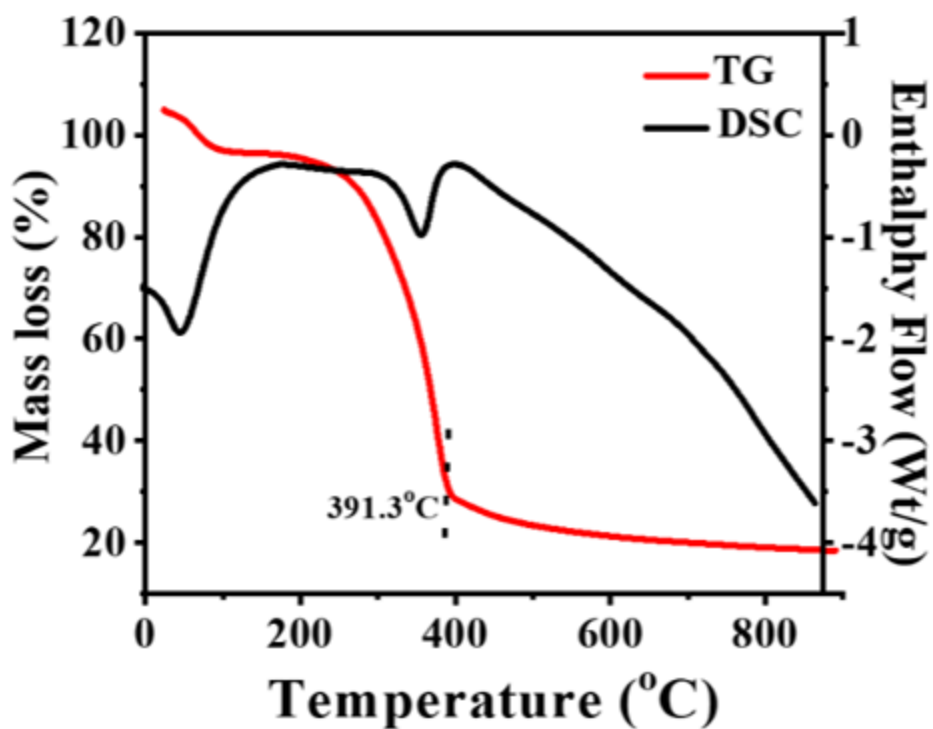


Figure 1

TGA/DSC plot of *Michelia Champaca* wood powder

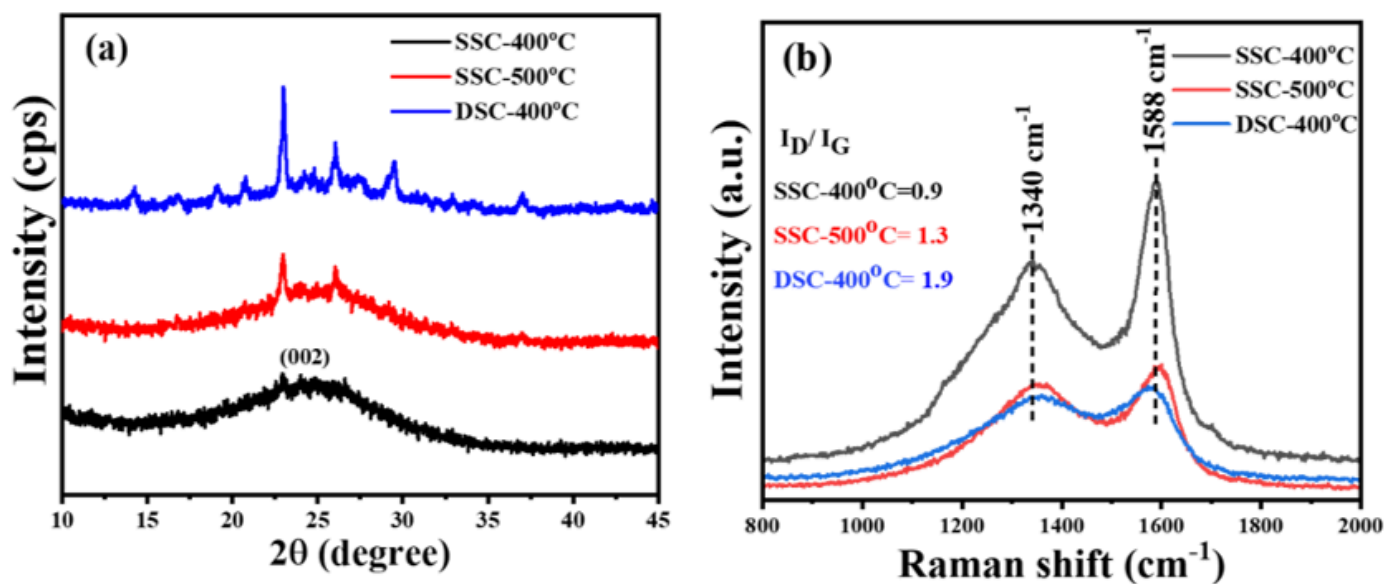


Figure 2

(a)XRD pattern and (b)Raman spectra of activated carbons

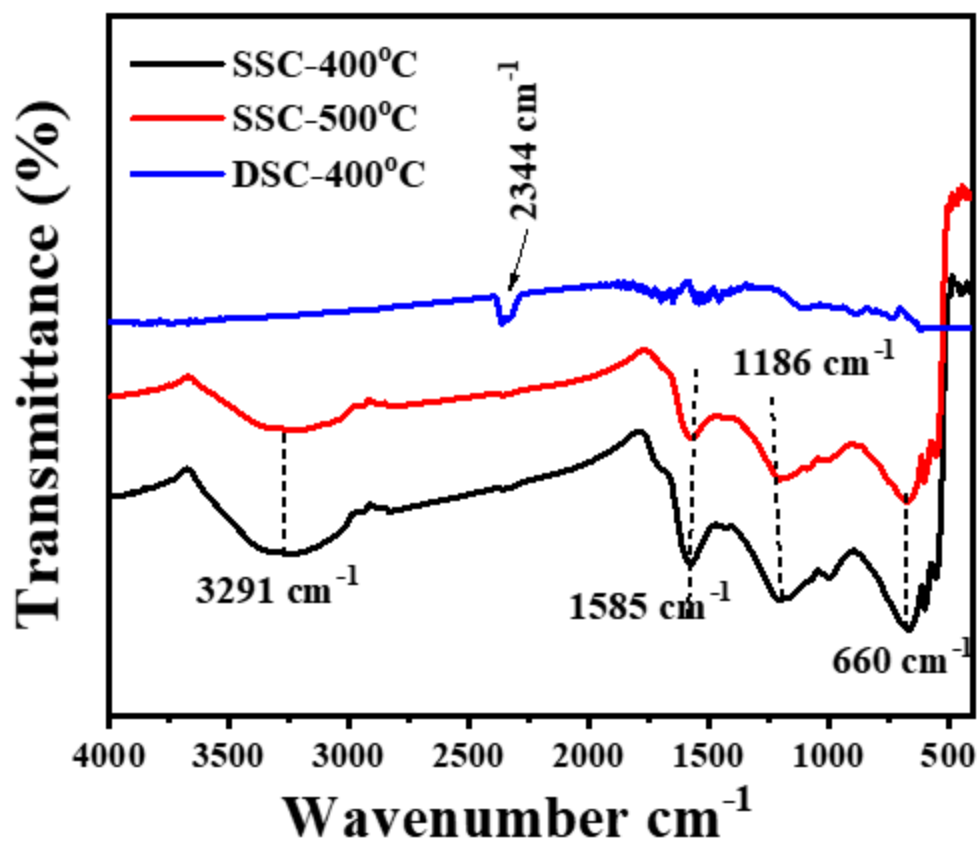


Figure 3

FTIR spectra of activated carbon samples

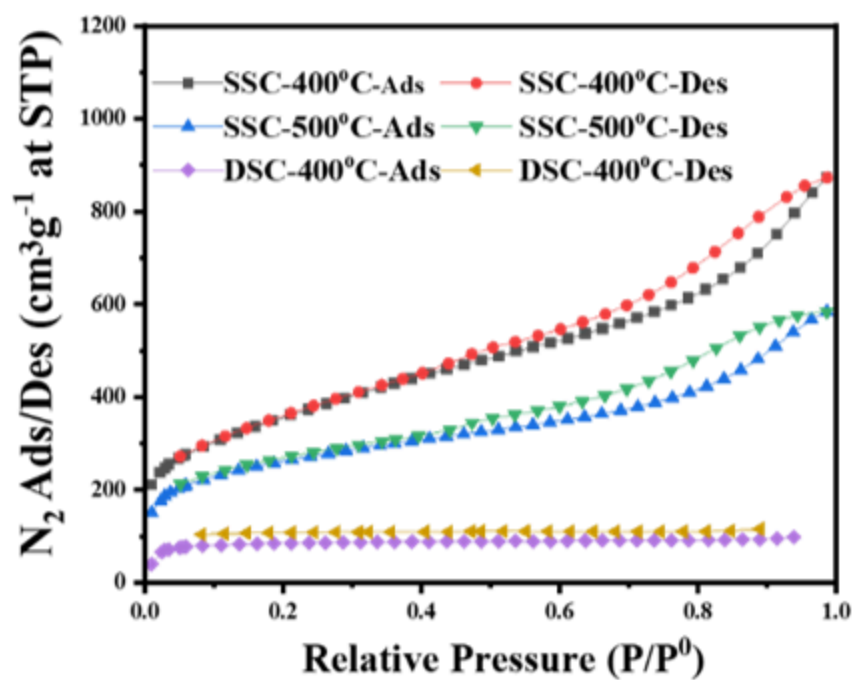


Figure 4

BET plot of activated carbon samples

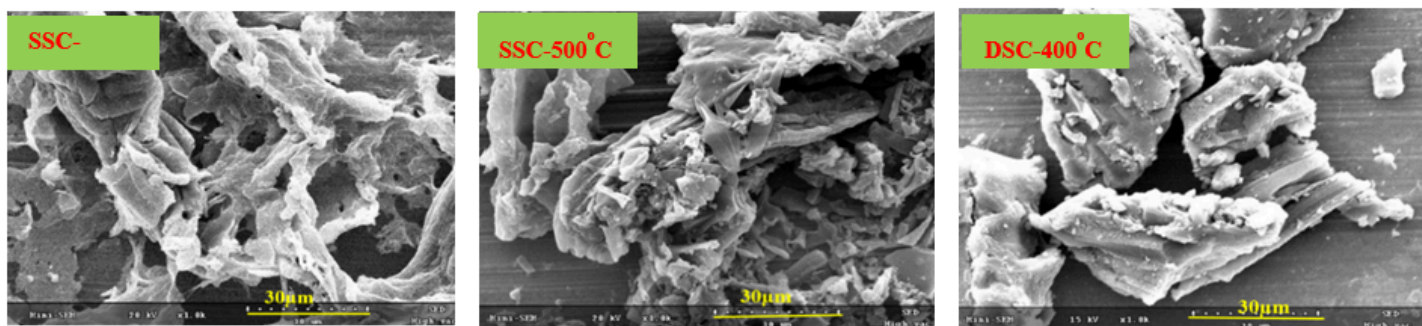


Figure 5

SEM images of activated carbon samples

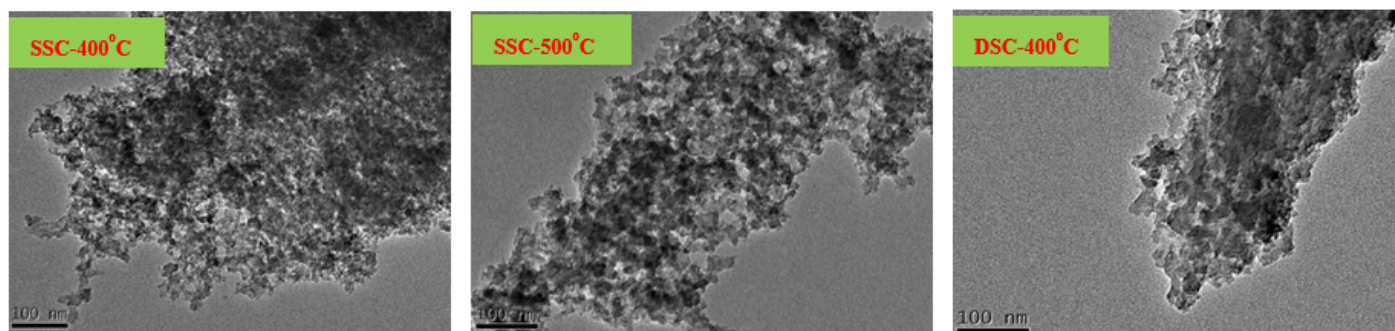


Figure 6

TEM images of activated carbon samples

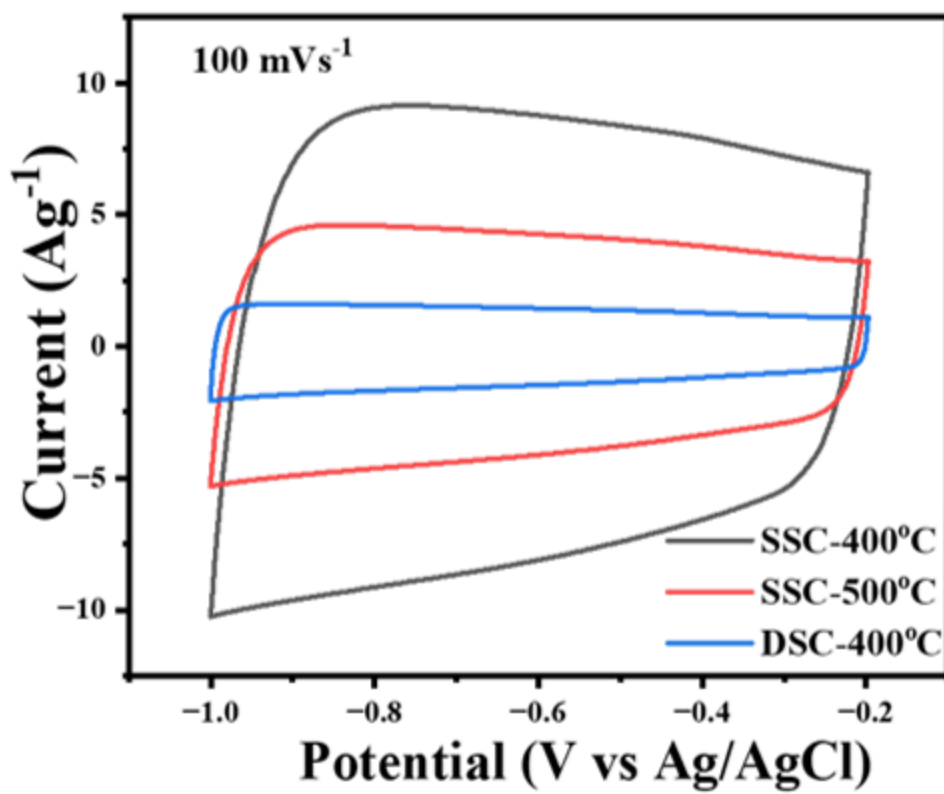


Figure 7

CV curves of activated carbon electrodes at (-1 to -0.2 V)

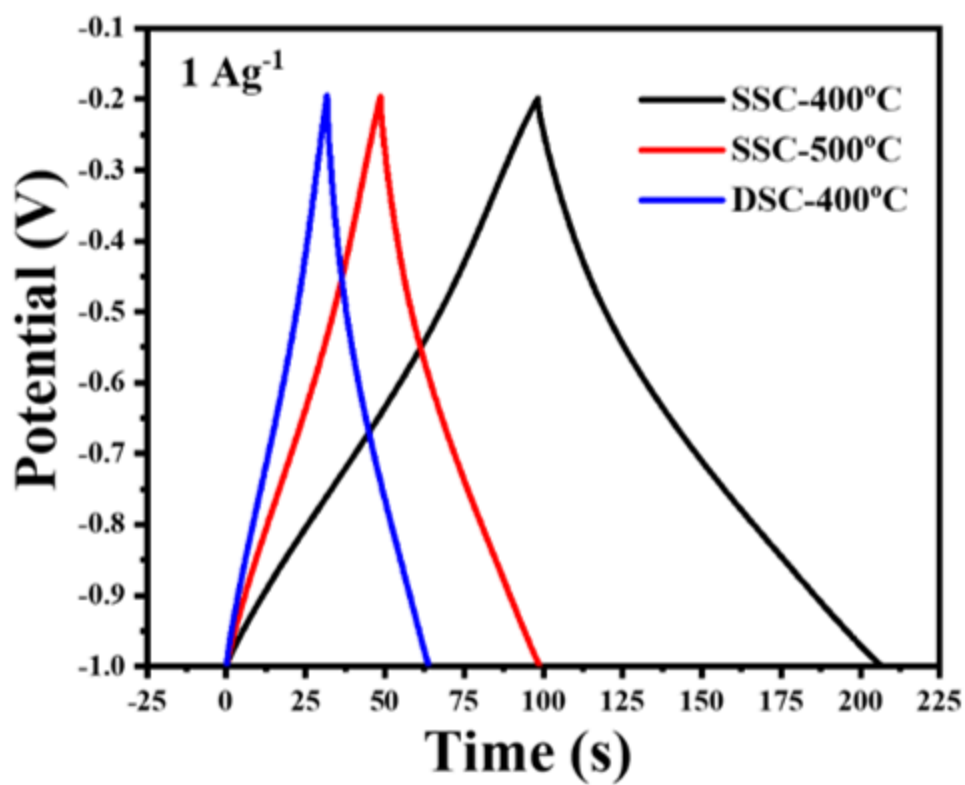


Figure 8

GCD curves of activated carbon electrodes at (-1 to -0.2 V)

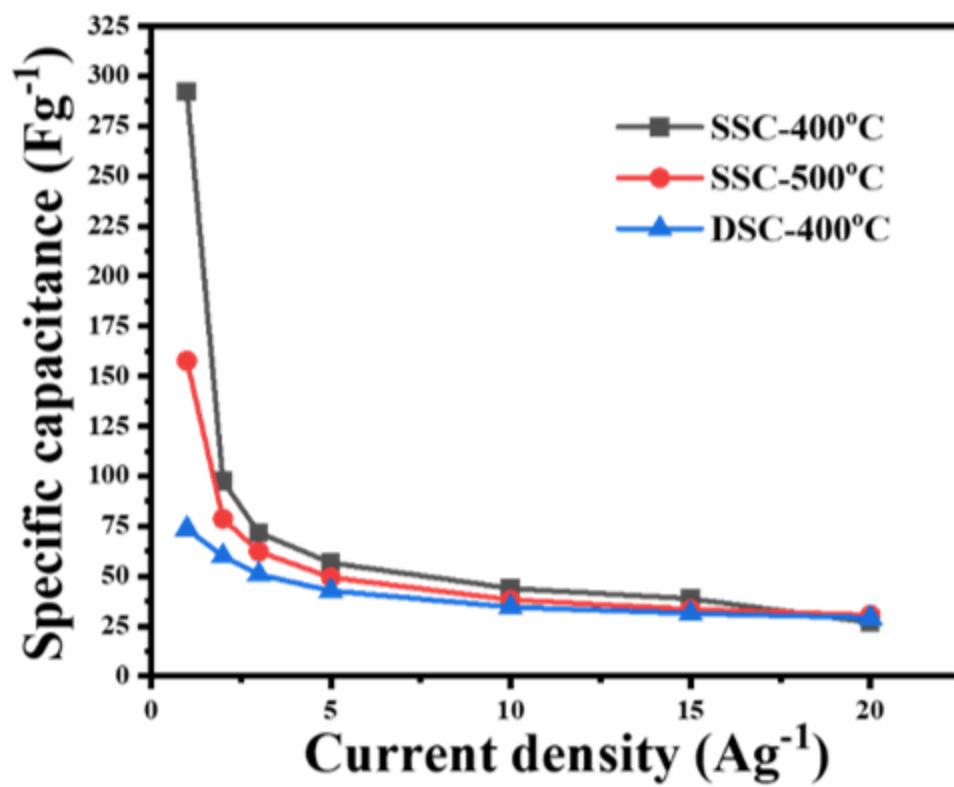


Figure 9

Specific capacitance of activated carbon electrodes Vs Current densities

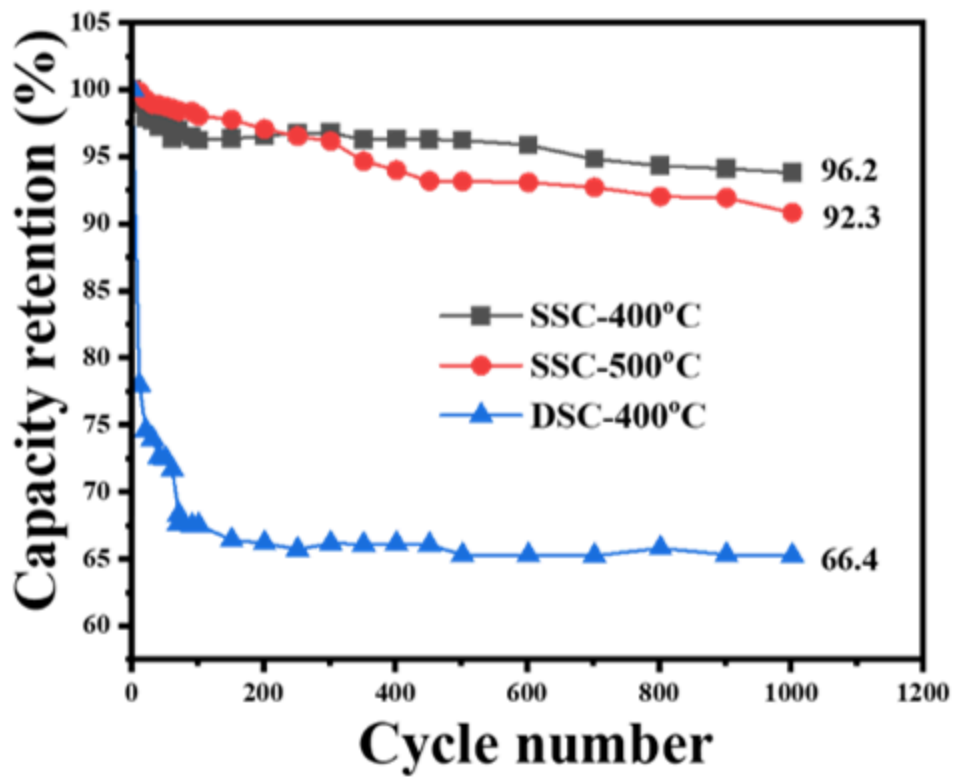


Figure 10

Fig. 9: Capacity retention (%) of activated carbon electrodes as a function of cycle number

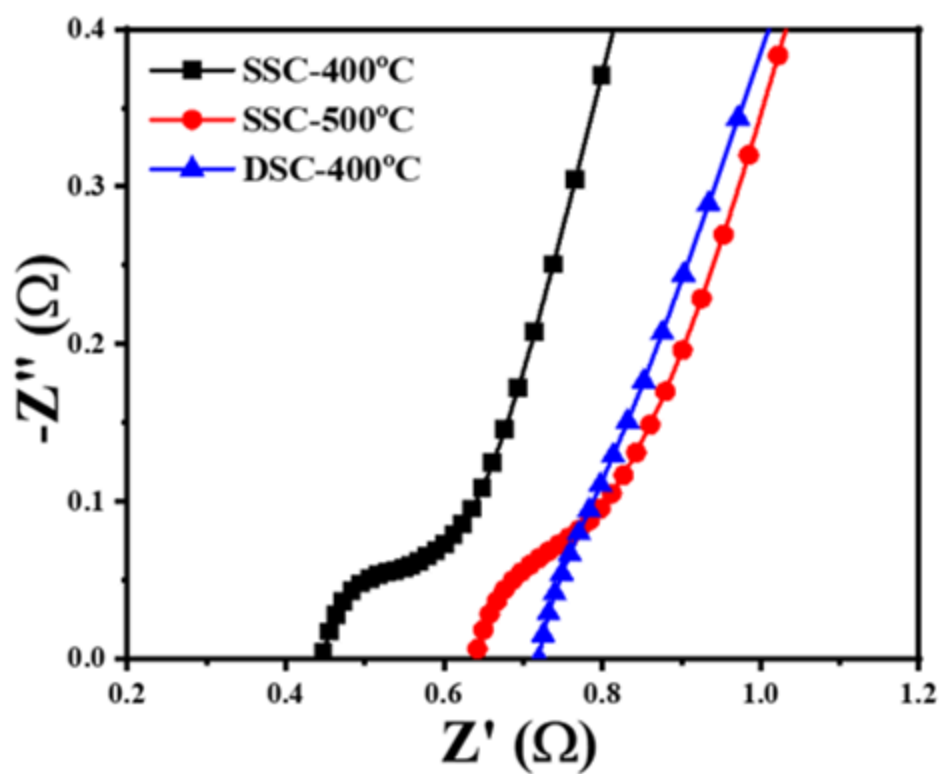


Figure 11

Fig.10:Nyquist plots of activated carbon electrodes

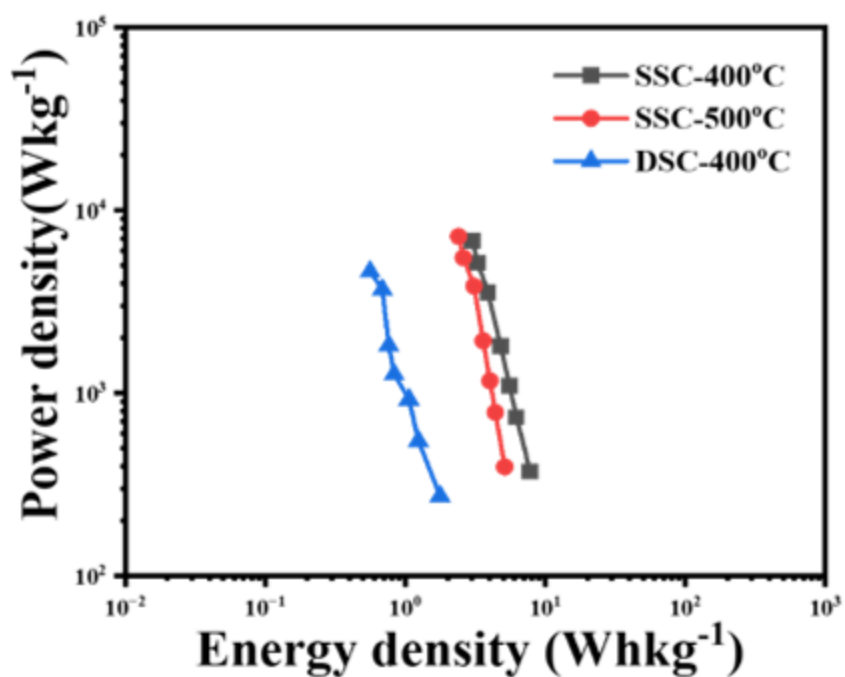


Figure 12

Fig.11: Ragone plot comparing energy density and power density of activated carbon electrodes

