Extraction of Carbon from Biomass-Based Bamboo and Coconut Husk for Enhancement of High-Performance Supercapacitor

Giriraj Dandekar, Gauresh Godkar, Omkar Salvi, Brijeshkumar Yadav, Mahadev Sonavane, and Rounak Atram

1 Introduction

Nowadays, everything is powered by electricity, including your mobile phone, laptop, and so on. As a result, a range of energy technologies, including traditional fossil fuels and sustainable options like solar panels, are employed globally to meet the growing energy demand. However, with the rapid increase in population and energy consumption, the importance of green energy has become paramount [1, 2]. To meet these demands, energy storage devices like batteries, capacitors, supercapacitors, and fuel cells are crucial. While batteries can store energy, they cannot charge rapidly, and capacitors, while quick to charge, have limited storage capacity [1, 3]. To overcome these limitations, researchers have turned to supercapacitors as a promising solution. The supercapacitor is a one-of-a-kind energy storage technology that outperforms batteries in a variety of ways. It is an electrochemical device with a high energy density, power density, and capacity, allowing it to charge faster and store more energy than batteries. Supercapacitors have many advantages, including a fast cycle rate, high power density, durability, extended life, and environmentally benign operation. Supercapacitors have wide-ranging applications in various fields, including the military, electric vehicles, and the medical sector, among others [4]. Based on their charge-storing mechanism, supercapacitors are divided into two types: Electric Double Layer Capacitors (EDLC) and Pseudocapacitors. EDLC stores charge faradaically, whereas Pseudocapacitors stores charge non-faradaically.

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Carbonaceous materials such as Graphene, CNT, CNF, biomass-derived carbon, and rGO are typically utilized as EDLC electrode materials, whereas metal oxides and conducting polymers are employed as Pseudocapacitors electrode materials [1, 3]. The properties of the electrode material and the electrolyte heavily influence the optimal performance of a supercapacitor [5, 6]. The surface area and pore size of the electrode material, in particular, are significant parameters influencing energy storage capacity and charge transfer efficiency [7, 8]. Carbonaceous materials such as graphite, carbon fibers, and carbon nanotubes have been intensively explored as possible electrode materials for supercapacitors, as have more recent innovations such as graphene, carbon black, activated carbon, biochar, hollow spheres, and mesoporous carbon [5, 7]. Biomass-derived carbon is a significant area of research due to its low cost, abundance, and renewable nature and may be extracted from a variety of biomass wastes [1, 3, 5]. In this study, we focus on comparing biomass-derived carbons from Bamboo and Coconut husk, specifically as electrode materials for supercapacitors. Both materials were chosen for their vast availability and unique properties: Bamboo has a high absorption capacity and extraordinary porous microstructure, while Coconut husk is an extremely fibrous material [9, 10]. The morphological and electrochemical properties of the biomass-derived carbons (BB-400 and CHB) were analyzed through various characterizations. Our results indicate that BB-400 demonstrates favorable electrochemical behavior and could be a promising candidate for supercapacitor applications.

2 Experimental

The pyrolysis and activation of waste biomass materials were performed in lab-scale facilities. The grade of the used chemicals was Analytical and was employed without further purification.

2.1 Sample Preparation

The parts of Bamboo and Coconut husk were collected from the campus of Bhavan’s College, Andheri (w), Mumbai, India. After that, both were fragmented into smaller pieces and dried in sunlight until all visible moisture had evaporated [11–13].

2.2 Preparation of BB-400

These collected samples were washed thoroughly with distilled water to remove adhering soil and dust and dried at 125 °C in a Hot Air Oven for 3 h. The next step was to initiate the torrefaction process in the Muffle Furnace at 250 °C for 3 h, after

Fig. 1 Schematic showing preparation of BB-400

which the material was cooled overnight [11–13]. Subsequently, the sample was ground using a mortar and pestle and filtered through layers of cloth. Then, the same filtered sample was placed in silica crucibles and enclosed with numerous layers of aluminum foil to minimize interaction with ambient air except air trapped between gaps of vessels and material being physically activated, resulting in a low-oxygen environment [14]. Now, these samples were filled in tightly sealed crucibles and this setup was put into Muffle Furnace at 400 °C for 2 h for carbonization. [14] (Fig. 1).

2.3 Preparation of CHB Carbon

After we collected the raw CHB, it was kept in a hot air oven for 3 h at 1100 °C for the moisture removal process. Then, CHB was crushed into fine pieces in a mortar and pestle and filtered through layers of cloth. Torrefaction was then initiated for 2 h at 200 °C in a Muffle Furnace. Finally, the carbonization was carried out in a Muffle Furnace for 2 h at 400 °C. It was accompanied by a restricted supply of oxygen. Thus, we extracted the carbon [15] (Fig. 2).

3 Characterization

To study the morphological structure and topology of the samples, such as roughness or smoothness, the samples were examined under a scanning electron microscope (SEM EVO 18, Carl ZEISS, Department of Physics, RTM Nagpur University, India.

Fig. 2 Schematic showing preparation of CHB carbon

The Electrochemical Analysis of BB-400 and CHB Carbon was carried out to determine the performance of the materials. The electrochemical properties of the materials were studied using Cyclic Voltammetry (CV), Galvanostatic Charge Discharge (GCD), and Electrochemical Impedance Spectroscopy (EIS) on the potentiostat in a 1 M H_2SO_4 electrolyte using a three-electrode device with Ag/AgCl serving as the reference electrode, platinum serving as the counter electrode, and the synthesized carbon materials serving as the working electrode.

4 Result and Discussion

4.1 Scanning Electron Microscopy

The SEM images of both materials revealed distinct morphologies. The BB-400 (Fig. 3a) derived carbon material exhibited random-sized pores distributed all over the surface and an excellent interconnected wire fence-like structure. In contrast, CHB-derived carbon showed a rough surface with the occurrence of an agglomeration of bulky particles with tiny and irregular pores between them. These SEM images confirm the previously reported literature that bamboo-derived carbon has a high absorption capacity and extraordinary porous microstructure [9]. This comparison of SEM images for BB-400 and CHB-derived carbon sheds light on the impact of

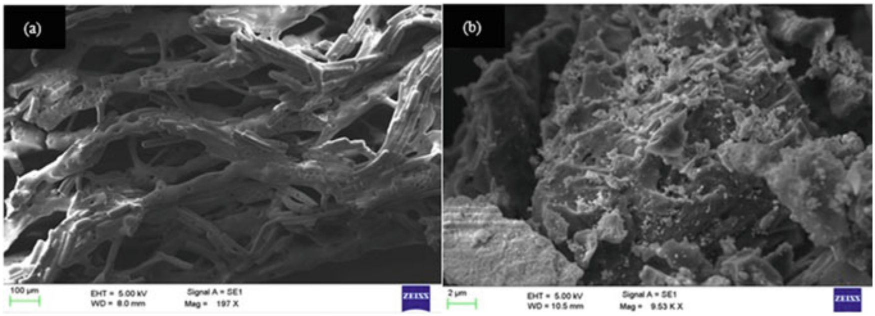

Fig. 3 SEM image of **a** BB-400 at a magnification of 197X, **b** CHB carbon at a magnification of 9.53KX

precursor biomass on the morphology and, therefore, the performance of carbon-based materials. This comparison shows that the biomass used for carbonization has a considerable impact on the shape of the produced carbon material and, as a result, the electrochemical performance of supercapacitor electrodes [5, 7].

4.2 Cyclic Voltammetry

The CV studies were conducted utilizing a three-electrode setup. To assess the capacitance behavior of the materials, CV measurements were performed at different potential windows and scan rates. BB-400 material displayed an almost ideal capacitive behavior, as evidenced by the nearly rectangular shape of the CV curves [16–18]. However, at higher scan rates of 75 mV/s, the CV curves showed some deviations from the ideal rectangular shape, indicating a quasi-rectangle shape at lower scan rates. Despite this, the shape of the CV curve remained unchanged at higher scan rates, suggesting a high degree of chemical stability of the material [19, 20]. In contrast, the CHB carbon also exhibited a quasi-rectangular-like shape in the CV curves, with two redox peaks observed at 0.5 V and 0.3 V. Interestingly, there was a significant increase in the area of the current from 10 mV/s to 100 mV/s, indicating that the material is highly conductive [21]. Furthermore, the oxidation peaks shifted to the right, while the reduction peak shifted to the left with increasing scan rates, which suggests that the material may have a higher resistance to oxidation than reduction [18, 21] (Fig. 4).

4.3 Galvanostatic Charge Discharge

The Galvanostatic Charge Discharge (GCD) analysis of BB-400 showed promising results in terms of its capacitive performance for supercapacitor applications. The

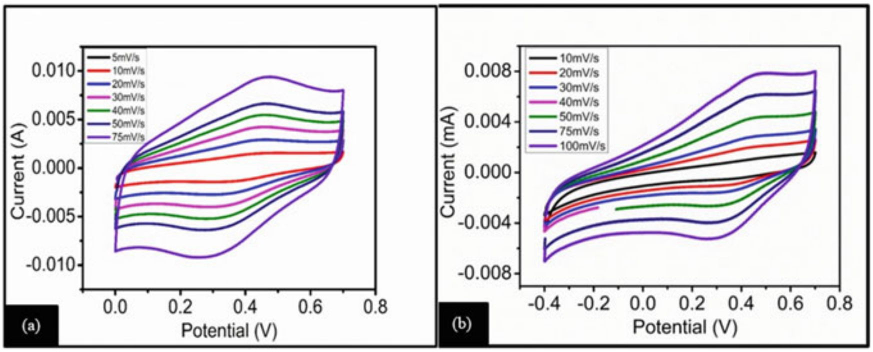

Fig. 4 Cyclic voltammetry of **a** BB-400, **b** CHB carbon

GCD curve exhibited a perfect triangular shape without any IR drop, indicating the reversible nature of the sample and its chemical stability. This behavior is crucial for the long-term stability and reliable operation of supercapacitors [18]. Based on the results of the GCD curves in Fig. 5, the specific capacitance values of the BB-400 were computed. Moreover, the specific capacitance of BB-400 was found to be higher at lower current densities, achieving a maximum value of 188.36 Fg^{-1} at 0.50 Ag^{-1}. However, the specific capacitance decreased to 87 Fg^{-1} at a higher current density of 7 Ag^{-1}. This behavior suggests that BB-400 exhibits good capacitive retention at higher current densities, making it an excellent candidate for high-performance supercapacitors [21]. CHB carbon also showed a standard triangular shape, with a plateau region observed in the potential window range of −0.3 to −0.4 V at a lower current density of 0.5 Ag^{-1}. This behavior is due to a slow charge adsorption of the material, indicating low electrolyte penetration at lower current density [22, 23]. However, at higher current density, no plateau region was observed, suggesting a highly conductive nature of the material. On the other hand, CHB carbon showed a higher specific capacitance of 124 Fg^{-1} at of current density of 1 Ag^{-1}, this value drops to 27 Fg^{-1} at a current density of 5 Ag^{-1}. The discharging time of GCD curves for both materials decreased with increasing current densities [24, 25]. From the description of the GCD curves, it can be concluded that BB-400 is a more suitable material for high current density applications due to its good capacitive retention, while CHB carbon is suitable for low current density applications due to its slow charge adsorption behavior [24].

The specific capacitance of BB-400 and CHB carbon was calculated by [23, 25]

$$C_s = \frac{I \times \Delta t}{m \times \Delta V} \tag{1}$$

where I (in A) is the discharge current, Δt (in s) is the discharge time, ΔV (in V) is the change in working potential and M (in g) is the mass of material.

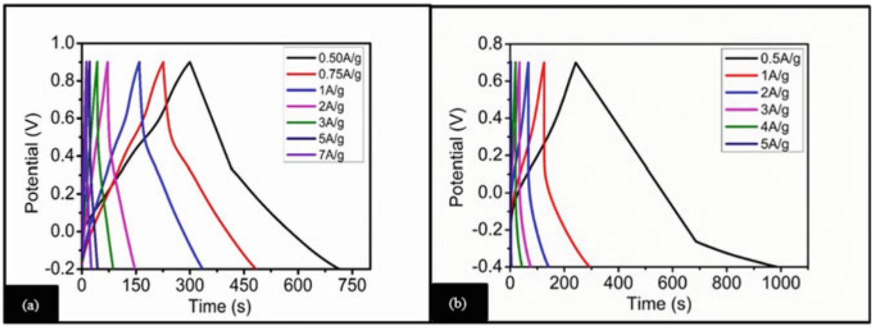

Fig. 5 GCD curves of **a** BB-400, **b** CHB carbon

4.4 Electrochemical Impedance Spectroscopy

EIS measurements were performed on both BB-400 and CHB carbon electrodes to investigate their resistive behavior and these results show that BB-400 and CHB carbon exhibit significant differences in their electrochemical properties. For BB-400, EIS measurements were conducted in the frequency range of 1 MHz to 1 MHz and a small distorted semicircle was observed. This semicircle can be attributed to the charge-transfer process at the electrode–electrolyte interface. The steeper slope in the lower frequency regime indicates that BB-400 has low diffusive resistance of electrodes due to fast ion diffusion [26]. On the other hand, for CHB carbon, EIS measurements were performed in the frequency regime of 0.1–100 kHz. The high-frequency intercept at the real part (Z') indicates the combinational resistance, including the ionic resistance of the electrolyte, intrinsic resistance of active material, and contact resistance of active material and current collector [23, 26]. A semicircle of ~225 Ω was observed in the intermediate frequency region of the Nyquist plot. As we know, the size of the semicircle is directly proportional to the charge transfer resistance (R_{ct}). Therefore, the smaller the semicircle, the faster the charge transfer kinetics of the material [23] (Fig. 6).

This semicircle observed for CHB carbon indicates that the charge transfer resistance at the electrode–electrolyte interface is significant. This means that the transfer of charge is not as efficient as in BB-400, and there is a higher chance of losing energy during the transfer process. Whereas the low charge transfer resistance of BB-400 makes it a promising material for supercapacitor applications.

4.5 Ragone Plot

A Ragone plot, which displays the relation between energy density and power density, can be used to compare the performance of different supercapacitor materials. At low power densities, CHB carbon has the maximum energy density of 5.2 Whkg^{-1}

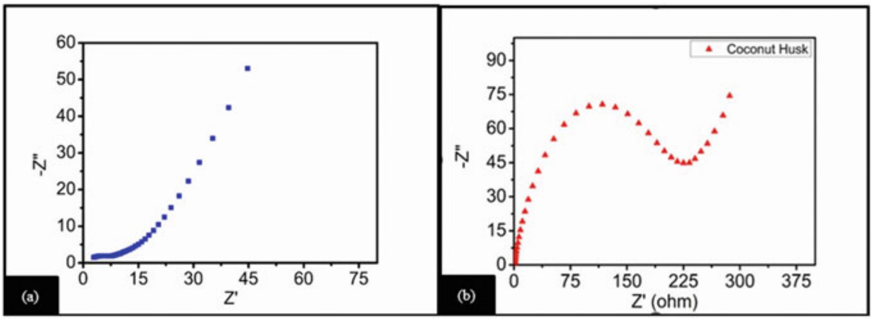

Fig. 6 Nyquist plot of **a** BB-400, **b** CHB carbon

at a power density of 68.57 Wkg^{-1}. However, when the power density grows, the energy density of CHB carbon declines substantially, reaching 1.13 Whkg^{-1}at the greatest power density of 271 Wkg^{-1}. As opposed to CHB carbon, BB-400 achieves a greater energy density at higher power densities, with a 3.67 Whkg^{-1} energy density at a 963.67 Wkg^{-1} power density. Results indicate that both materials have their advantages and disadvantages in terms of power and energy density. CHB has a high energy density at low power densities, however, this energy density cannot be maintained at greater power densities. BB-400, on the other hand, has a lower energy density at low power densities but can sustain a reasonably high energy density at higher power densities [27–29]. These statistics are significant because they emphasize how crucial it is to select the right material for each individual application when using supercapacitors. For example, if the application demands a high energy density at a low power density, CHB carbon may be the ideal option. But, BB-400 could be a better option if the application requires a high-power density at higher energy densities (Fig. 7).

The ED and PD of BB-400 and CHB carbon were calculated by [3, 6, 23]

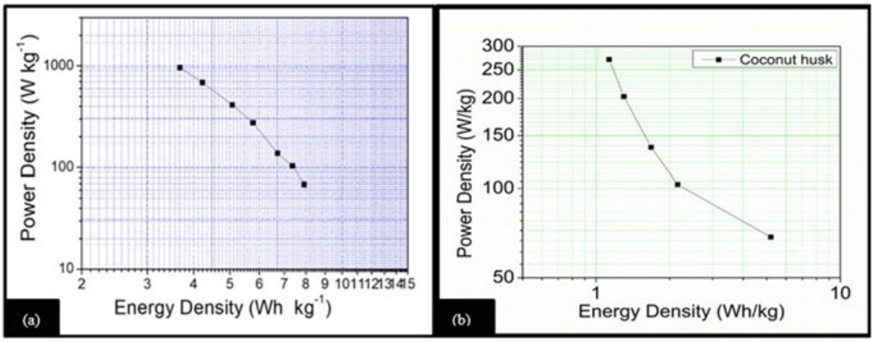

Fig. 7 Ragone plot of **a** BB-400, **b** CHB carbon

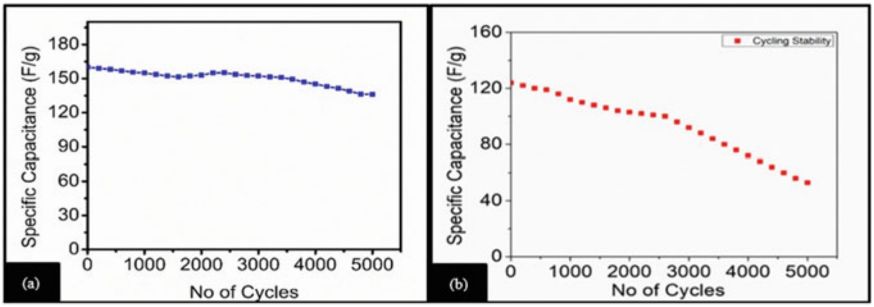

Fig. 8 Cyclic performance of **a** BB-400, **b** CHB carbon

$$Energy\ Density(ED) = \frac{1}{2 \times 3.6} \times C_s \times V^2 \tag{2}$$

$$Power\ Density(PD) = \frac{3600 \times ED}{\Delta t} \tag{3}$$

4.6 Cycling Stability

Cyclic stability is a crucial factor to take into account when assessing the effectiveness of supercapacitors for real-world applications. It refers to a supercapacitor's ability to sustain capacitance and charge storage capacity through repeated charge–discharge cycles. In this regard, a number of variables, including the materials used in the fabrication of electrodes, electrolytes, the operating voltage range, and the charging/discharging current density, might impact the cyclic stability [26]. The results showed that both materials exhibited a reduction in capacitance during their initial phases of the cycling test. However, BB-400 revealed amazing stability even after 5000 cycles with over 80% retention, but CHB carbon showed a considerable decline in retention after 3000 cycles. This implies that the BB-400 is more suited for long-term energy storage applications that demand steady and consistent performance through several cycles (Fig. 8).

5 Conclusion

In this work, the carbon from bamboo biomass and coconut husk biomass was successfully prepared using the carbonization method. SEM images showed BB-400 has a greater porosity than CHB carbon. Using characterization techniques like CV, GCD, and EIS, the electrochemical performance of carbon electrodes made from BB-400 and CHB was assessed. The BB-400 demonstrated improved electrochemical performance and great stability from the CV curves. At a current density of 1Ag^{-1}, CHB demonstrated a high specific capacitance of 124 Fg^{-1} and demonstrated about 60% stability after 5000 charge and discharge cycles. The CHB carbon has a high power density of 271 Wkg^{-1} as well as a high energy density of 5.2 Whkg^{-1}. A high specific capacitance of 188.36 Fg^{-1} at 0.50 Ag^{-1} of current density was demonstrated by the BB-400. Moreover, it has a high power density of 963.67 Wkg^{-1} and a high energy density of 7.91 Whkg^{-1}. It has shown a good performance of 80% for Electrochemical Cyclic Stability at 5000 cycles. Proving that carbon extracted from bamboo is an excellent material for supercapacitors.

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