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Physical and electrochemical properties of activated carbon derived from bamboo charcoal utilizing diverse electrolytes for supercapacitor applications: A review

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ABSTRACT

Activated carbon is a highly porous material that is widely used in energy applications, such as supercapacitors, as it has a large specific surface area and good electrical conductivity. Bamboo, as one of the abundant biomasses, can be processed into high-quality activated carbon through chemical activation process. With its natural carbon-rich structure and pores, bamboo provides a great opportunity to improve the energy storage performance of supercapacitors. This study analyzes the physical and electrochemical properties of activated carbon synthesized from bamboo charcoal using KOH activation for supercapacitor applications. Structural characterization was performed using X-ray diffraction and field emission scanning electron microscopy, which showed an amorphous structure with high porosity. Electrochemical studies via cyclic voltammetry and galvanostatic charge-discharge revealed that the electrolyte mixture (Na_2SO_4 1 M and KOH 0.5 M) yielded the best performance with a maximum specific capacitance of 290 F/g at a current density of 1 A/g. These results indicate that bamboo-based activated carbon has great potential for environmentally friendly energy storage applications.

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1. INTRODUCTION

Efficient and renewable energy sources have become imperative due to the rampant combustion of fossil fuels and escalating environmental degradation. Efficient, eco-friendly energy storage and conversion systems are regarded as one of the most critical solutions to these issues. Supercapacitors (SC) have lately garnered significant attention among various energy storage technologies due to their numerous advantages in electrochemical performance [1]. Biomass serves as an optimal supply of carbon electrode materials for supercapacitors owing to its affordability, abundant availability, and eco-friendliness. Biomass is abundant in elemental carbon, promoting enhanced carbon production. Its inherent porous structure endows the resultant carbon material with an exceptional specific surface area and a well-developed pore architecture, facilitating the diffusion of electrolyte ions. The benefits of carbon electrode materials generated from biomass indicate significant potential for their application as electrodes [2].

Bamboo is a biomass with potential applications as electrodes. Bamboo leaves are desiccated in an oven to produce bamboo charcoal, which may serve as a high-quality and efficient activated carbon material for supercapacitor applications, activated using the solvent KOH. The features of activated carbon, including texture, morphology, and surface chemistry, can be analysed using various analytical techniques and methodologies in conjunction with different aqueous electrolytes.

2. THEORITICAL REVIEW

2.1. Bamboo

Bamboo is a group of woody grasses that belong to the Poacea family. The lightweight and flexible nature of its stems makes it suitable for use in civil construction, the shoots of some species can be consumed as food and energy from bamboo biomass has also been assessed. In electronics, residual bamboo can be used like a carbon source to provide supercapacitor performance [3].

Figure 1. Bamboo biomass.

Table 1. Chemical composition of bamboo biomass.

Components	%
Carbon	45.3-47.6
Cellulose	42.4 - 53.6
Lignin	19.8 - 26.6
Pentosan	1.24 - 3.77
Ash	1.24 - 3.77
Silica	0.10 - 1.78

2.2. Capacitors

Capacitors are passive electrical components that store energy in an electric field. The capacitor comprises two conducting plates with opposing charges, each with a surface area of A. The conductors are distanced from one another by a dielectric that functions as an insulator. The cumulative charge on the surfaces of the conductor is null. This is due to the equality of negative and positive charges. Dielectric materials are insulators in the absence of an electric field. Nonetheless, when an electric field traverses it, an electric dipole will emerge, and the orientation of the magnetic field will be antipodal to the initial electric field [4].

2.3. Supercapacitors

Supercapacitors are a novel category of energy storage devices characterised by high capacitance, elevated power density, operational efficacy throughout a broad temperature spectrum, and extended durability. A comparison of several energy storage devices is presented in (Figure 3.a). Supercapacitors comprise two electrodes, an ion-permeable membrane referred to as a separator, a current collector, and an electrolyte that facilitates ionic connectivity between the electrodes. A combination of aqueous and organic electrolytes, such as H2SO4 and KOH, can enhance the electrochemical performance of supercapacitors

The operational basis of an electrochemical capacitor, sometimes referred to as a supercapacitor, involves the attraction of oppositely charged ions to the current collector or metal plate upon the application of voltage. Subsequently, ions from the electrolyte accumulate on the surface of the collector, thereby generating a charge.

2.4. Physical Properties of Cell Electrodes in Supercapacitors

The physical properties of supercapacitor cell electrodes can be examined using many techniques, including X-ray diffraction (XRD) and field emission scanning electron microscopy with energy dispersive spectroscopy (FE-SEM EDS).

2.4.1. X-Ray Diffraction (XRD)

X-ray Diffraction is a technique employed to ascertain the atomic and molecular structure of crystals by dispersing X-ray rays in many directions. The XRD tool functions to identify and analyse the phase or state of materials in solid or powder form from inorganic samples that are amorphous or polycrystalline.

2.4.2. Field emission scanning electron microscope (FE-SEM EDS)

FE-SEM is a tool used for fractographic analysis. FE-SEM also serves to look at the morphology of microstructure such as grain shape and grain size; look at the texture of the grain surface such as looking at the crystallographic orientation of the material and the phase difference of the material.

3. MATERIALS AND METHOD

3.1. Electrochemical Characteristics of Supercapacitor Cells

The electrochemical characteristics of supercapacitor cells can be assessed using techniques such as Cyclic Voltammetry (CV) and Galvanostatic Charge Discharge (GCD).

3.2. Cyclic Voltammetry (CV)

Cyclic voltammetry is an electrochemical technique utilised to assess the efficacy of electrical energy storage systems. This technique involves applying a periodically and linearly varying electric field to the electrodes. The current at the working electrode is graphed against the applied voltage to generate a cyclic voltammogram depicting the current versus voltage trace. Both forward and backward scans are necessary to forecast oxidation and reduction peaks. The interplay of salts and solvents in the electrolyte, along with the active elements in the working electrode, dictates the potential windows for cyclic voltammetry observations. The accumulation of charge on the electrode surface can be determined by integrating the electric current over time. Furthermore, capacitance can be calculated by dividing the charge by the operational potential range [9].

3.3. Galvanostatic Charge-Discharge (GCD)

The charge stored in the material is assessed using GCD techniques. The theory is that by supplying a constant current, the electrode will absorb and retain charge, resulting in an increase in potential. A suitable current will be implemented when the voltage reaches a specified threshold. The discharge occurs, resulting in a decrease in potential. The graphical representation varies according on the energy storage technique. The slope of the voltage versus time curve is variable (nonlinear relationship) when the mechanism entails charge conversion via redox reactions [10].

3.4. Synthesis of Activated Carbon from Bamboo Leaf Charcoal

Bamboo leaves were produced by a chemical reaction process. The bamboo leaves were rinsed with deionised water and baked in an electronic oven at 80°C for 24 hours, resulting in bamboo charcoal powder. The desiccated samples were initially carbonised in a controlled furnace maintained at 300°C for a duration of 3 hours. The bamboo leaf charcoal was initially carbonised with a KOH mixture in a 1:3 ratio with the produced material. The KOH mixture sample was agitated with deionised water for a duration of 24 hours. The samples were filtered and collected for activation in a tubular furnace maintained at 800 C in an argon environment for 2 hours. The product was subsequently centrifuged multiple times with 1 M HCl and deionised water to eliminate contaminants. The produced samples were subjected to processing in an electron oven at 80°C for 24 hours to yield activated bamboo charcoal powder.

4. RESULTS AND DISCUSSIONS

4.1. Examination of the Physical Properties of Bamboo Charcoal Activated Carbon

The amorphous structure and phase purity of bamboo charcoal activated carbon materials were examined using X-ray diffraction (XRD). The morphological characterisation of the material surface was conducted using FE-SEM, with EDS employed to identify elements and compounds in the activated carbon material. Figure 2 presents the X-ray diffraction (XRD) spectrum analysis, indicating the carbon peak at refraction angles of 26.6° and 43.3°, corresponding to the lattice planes (002) and (102). This also corroborates the presence of the graphite carbon peak, with the pronounced (002) peak signifying a high graphite character.

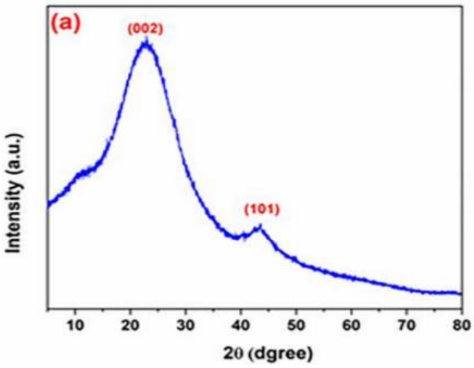

Figure 2. X-ray diffraction pattern of activated carbon.

The surface morphology of bamboo charcoal activated carbon was examined via FE-SEM. Figure 3 illustrates the morphological characteristics of activated bamboo carbon material as analysed by FE-SEM. The morphology exhibits a porous behaviour characterised by an uneven and heterogeneous structure, with pore sizes ranging from 5 µm to 500 nm. The augmentation of the specific surface area of the carbon is attributable to the multitude of pores present on the surface of the bamboo leaf activated carbon. The openings this also facilitates the ingress of electrolyte ions into the activated carbon material. The charge capacity of the supercapacitor device will increase with a bigger specific surface area of the activated carbon.

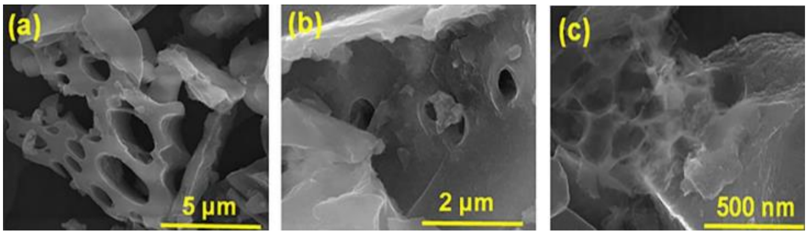

Figure 3. Illustrates the FE-SEM morphology of activated carbon.

The surface of bamboo leaf activated carbon, characterised by many pores, can be examined, and the elemental composition of bamboo leaf charcoal samples can be determined using EDS testing. The outcomes derived from the EDS test are displayed in Table 2 below.

Table 2. Percentage of elemental composition in bamboo leaf activated carbon.

Elemental	Mass Percentage (%)	Atomic Percentage (%)
C	13.84	21.66
O	38.31	45.00
Al	47.85	33.34
Total	100.00	100.00

The carbon element (C) in bamboo leaf activated carbon comprises 13.84% by mass and has an atomic concentration of 21.66%. Consequently, the carbon component in bamboo leaf activated carbon can serve as a fundamental material for the fabrication of supercapacitor electrodes. Bamboo leaf activated carbon contains oxygen with a mass percentage of 38.31% and an atomic percentage of 45.00%.Comprises Aluminium (Al) at 47.85%, with an atomic composition of 33.34%.

4.2. Examination of the Electrochemical Properties

The electrochemical characteristics of bamboo leaf charcoal activated carbon were examined using Cyclic Voltammetry (CV) and Galvanostatic Charge Discharge (GCD) or Constant Current (CP) methods.

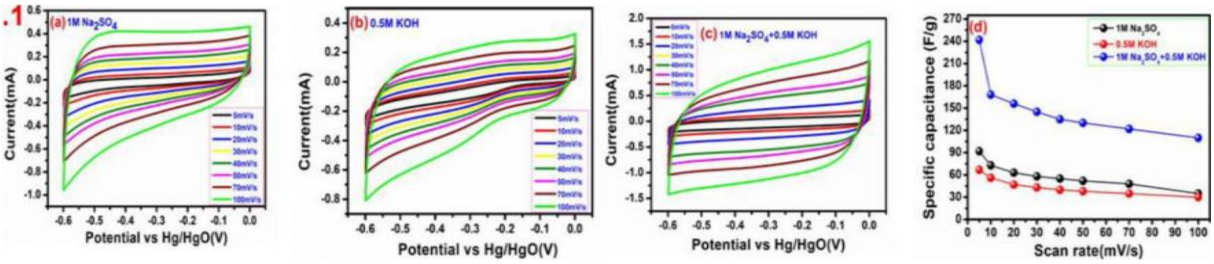

Figure 4. (a) Cyclic Voltammetry with 1 M solution Na_2SO_4 (b) CV with 0.5 M KOH solution (c) CV with 1 M solution Na_2SO_4 + 0.5 M KOH: d) scanning speed versus specific capacitance.

Figure 4 (a-d) illustrates the Cyclic Voltammetry (CV) profiles of activated carbon materials utilising distinct aqueous electrolytes: (a) 1 M Na_2SO_4, (b) 0.5 M KOH, and (c) a combination of 1 M Na_2SO_4 and 0.5 M KOH, across varying scan rates of 5, 10, 20, 30, 40, 50, 70, and 100 mV/s. Figure 4 (a) demonstrated that the cyclic voltammetry (CV) curve of activated carbon analysed with a 1 M Na2SO4 electrolyte solution exhibited characteristics akin to electric double layer capacitor (EDLC) behaviour at varying scan rates. The capacitance value was determined to be 100 F/g at a scan rate of 5 mV/s. Figure 4 (b) illustrates the cyclic voltammetry pattern of carbon material treated with a 0.5 M KOH electrolyte solution, exhibiting electric double-layer capacitor characteristics, with a specific capacitance of 80 F/g at a scan rate of 5 mV/s. Figure 4 (c) depicts the cyclic voltammetry pattern analysis of activated carbon utilising a mixture of electrolytes, specifically Na_2SO_4 at 1 M and KOH at 0.5 M, which functions similarly to a two-layer capacitor. The maximum specific capacitance recorded was 250 F/g at a scan rate of 5 mV/s. The curve generated is the Hysteresis Curve, which signifies the presence of charge on the electrode; a broader curve suggests a higher capacitance value. Augmenting the electrolyte concentration results in an increase in the charge stored within the supercapacitor device. Figure 4 (d) indicates that the aqueous electrolyte mixture of Na_2SO_4 1 M and KOH 0.5 exhibits superior electrochemical performance compared to other electrolytes. The higher the scan rate, the lower the capacitance value; thus, it can be stated that capacitance is inversely proportional to the scan rate. A high scan rate results in a reduced cycle time, leading to a diminished accumulation of electrolyte ions on the electrode surface. Conversely, if the scan rate is low and the one-cycle period is prolonged, a greater accumulation of electrolyte ions occurs on the electrode surface.

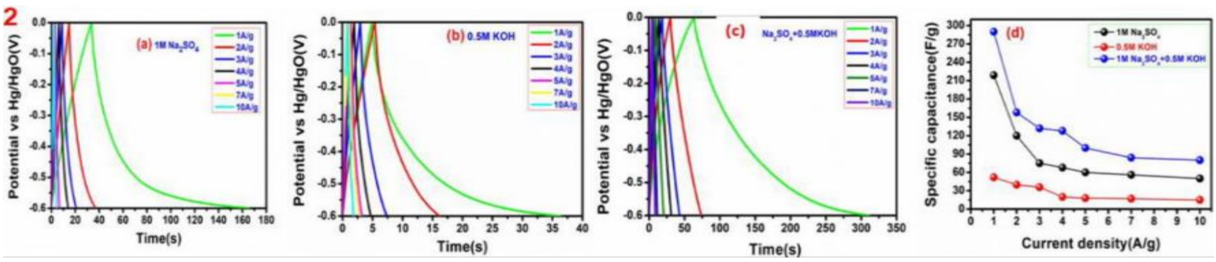

Figure 5. (a) GCD pattern of activated carbon with electrolyte Na2SO4 1 M (b) GCD pattern of activated carbon with electrolyte 0.5 M KOH; (c) GCD pattern of activated carbon with electrolyte 1 M Na2SO4 + 0.5 M KOH (d) current density vs specific capacitance.

Figure 5 (a-d) illustrates the charging and discharging pictures of activated carbon utilising various aqueous electrolytes at differing current densities. Figure 5 (a) illustrates the GCD pattern analysis of activated carbon utilising a 1 M Na_2SO_4 solution, revealing a substantial specific capacitance of 220 F/g at a current density of 1 A/g. Figure 5 (b) illustrates the GCD curve of activated carbon utilising a 0.5 M KOH electrolyte, revealing a specific capacitance of 100 F/g at 1 A/g, a noteworthy outcome compared to previously documented activated carbon results. Figure 5 (c) illustrates the cyclic voltammetry pattern of activated carbon utilising an electrolyte mixture of 1 M Na_2SO_4 and 0.5 M KOH, with a specific capacitance measured at 290 F/g at a low current density of 1 A/g. Figure 5 (d) illustrates the relationship between specific capacitance and current density utilising different electrolytes. The mixed electrolyte of 1 M Na_2SO_4 and 0.5 M KOH exhibits superior performance relative to the individual electrolytes.

5. CONCLUSION

Activated carbon sourced from bamboo leaves was effectively synthesised by a chemical activation process utilising KOH as the activating agent, and its physical and electrochemical characteristics were examined using diverse electrolytes. Electrochemical studies utilising Cyclic Voltammetry (CV) and Galvanostatic Charge-Discharge (GCD) demonstrated that blended electrolytes displayed enhanced performance relative to individual electrolytes. The GCD pattern demonstrated that the specific capacitance of the mixed electrolyte attained 290 F/g at a low current density of 1 A/g, but the CV pattern revealed a specific capacitance of 250 F/g at a scan rate of 5 mV/s, indicating superior electrochemical performance. Furthermore, augmenting the electrolyte concentration improved the charge storage capacity of the supercapacitor device. The GCD method is deemed more representative of capacitor performance in practical applications than the CV method, as it assesses charge and discharge operations under constant current conditions.

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