Synthesis and Characteristics of Bamboo-based Activated Carbon as Electrode Materials

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Abstract. The growing demand for sustainable energy storage solutions has intensified research into biomass-derived materials as eco-friendly alternatives to conventional components. Bamboo, a rapidly renewable and abundant resource, exhibits unique structural properties, making it a promising candidate for high-performance activated carbon. This study bamboo-based activated carbon was activated at 120°C to 160°C with potassium hydroxide for one hour, followed by extensive washing with deionized water and drying in a vacuum desiccator for 3 days. Characterization using scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and cyclic voltammetry (CV)measurements revealed its porous structure and functional diversity. Optimal performance was achieved at 7% KOH concentration and a scan rate of 75 mV/s, demonstrating a high specific capacitance and excellent cyclic stability with retention rate exceeding 90%. These results highlight bamboo's viability as a sustainable, high-performance electrode material, offering promising solutions for advancing green energy storage technologies.

1 Introduction

The growing need for efficient energy storage in renewable energy highlights the importance of developing affordable and sustainable materials. Biomass, especially waste-derived materials, offers a promising alternative to traditional battery and supercapacitor components. Around 137 million tons of biomass are produced daily worldwide, representing a largely untapped resource for sustainable energy [1]. Biomass is renewable and cost-effective, providing a way to create carbon materials with high surface area, porosity, and excellent electrical conductivity [2 -3]. Using biomass can also lower carbon emissions, helping combat climate change [4]. Among biomass sources, bamboo (Bambusa vulgaris) is notable for its rapid growth and unique structure, making it an ideal carbon source [5]. Bamboo charcoal has a much larger surface area compared to regular charcoal, enhancing its adsorption capacity [6]. Its abundance and low cost make bamboo charcoal a valuable material for energy storage applications [7].

Bamboo is commonly used in construction, textiles, and medicine due to its sustainability [8-9]. Recently, many studies have explored bamboo's role in flexible supercapacitors as it offers a sustainable and cost-effective alternative due to its naturally occurring hierarchical porosity, high carbon content, and ease of activation. For example, Gong et al. (2024) created porous bamboo-based ceramics for energy storage electrodes that achieved high capacitance [10]. Other studies demonstrated the effectiveness of bamboo-derived materials in producing carbon-based electrodes with impressive capacitance values [11-12]. Supercapacitors are efficient energy storage devices known for their quick charge and discharge capabilities. They rely on the electrode material's specific capacitance and voltage difference to determine energy density [13-14]. Eco-friendly materials like CoMoO4/bamboo charcoal composites have shown excellent performance in supercapacitors [15].

Integrating bamboo-based materials within this evolving landscape situates them as viable contenders for next-generation supercapacitor electrodes. Our results indicated that increasing KOH concentration and scan rate improved electrochemical performance, achieving optimal results at a 7% KOH concentration and a scan rate of 75 mV/s. Their renewable nature and ease of processing align with global sustainability goals, particularly for large-scale, low-cost energy storage applications.

2 Experimental

2.1 Materials

Activated bamboo carbon powder was purchased from HMVS Store, Polyvinyl alcohol (PVA), Carboxymethyl cellulose (CMC), Silicon carbide (SiC), Urea (CH N O), and Potassium hydroxide (KOH). Experimental tests were performed using DI (de-ionized) water.

2.2 Synthesis of Bamboo-Based Activated Carbon

To synthesize bamboo-based activated carbon, 70 g of activated bamboo carbon powder was dispersed in deionized water and mixed with 5 g of Polyvinyl Alcohol (PVA), and 5g of Carboxymethyl Cellulose (CMC). Once a homogeneous was achieved, 10g of graphite powder, 5 g of silicon carbide and 5 g of urea were gradually added to enhance the composite’s structural and conductive properties. The mixture was stirred continuously to ensure even distribution. The resulting mixture was cooled and moulded and subjected to drying at 60C for 12 hours in an oven. Subsequently, the sample underwent thermal activation in a potassium hydroxide (KOH) solution at temperatures ranging from 120°C to 160°C for one hour. Later, the sample was washed extensively with deionized water to remove any residual chemicals and dried in a vacuum desiccator for a minimum of three days.

2.3 Characterization of Bamboo-Based Activated Carbon

The morphology and structure of carbon samples was analyzed using scanning electron microscopy (SEM, Regulus 8100, Hitachi). The crystal structures were characterized by Xray diffraction (XRD, Rigaku MiniFlex II) andFourier transform infrared spectra (FTIR) measurements were conducted with a FTIR-4200 (JASCO) for surface functional group analyses.

2.4 Electrochemical Measurement

The electrochemical performance of the electrode was evaluated using a three-electrode system. A platinum plate and silver–silver chloride (Ag/AgCl) electrode was used as the working electrode and reference electrode, respectively. The three electrodes were immersed in KOH electrolyte solutions at concentrations of 3%, 5%, and 7%. Cyclic voltammetry (CV) measurements were performed by applying the electrode mixture onto a rotating disk electrode (RDE) rod at a potential scan rate ranging from 25 to 75 mV/s. Subsequently, the preparation of the electrode mixture involved blending the composite with water and a CMC binder, followed by sonication to ensure complete dissolution. This experimental analysis aimed to explore the structure-property relationships of bamboo-based activated carbon and assess its performance as an electrode material.

3 Result and Discussion

3.1 Characterization of Bamboo-Based Activated Carbon Electrode

Figure 1 identified critical functional groups such as hydroxyl (3155 cm^{-1}), aliphatic hydrocarbons (2851-2921 cm^{-1}), and carbonyl groups (1656 cm^{-1}), which contribute to electrochemical interactions. A broad peak around 3155 cm^{-1} signifies the presence of O-H groups, which are characteristic of hydroxyls and water commonly found in hydrogels. This broadness reflects a polymer network rich in hydrogen bonds. Peaks at 2851 cm^{-1} and 2921 cm^{-1} correspond to C-H stretching vibrations in aliphatic hydrocarbons, indicating the presence of methylene (-CH_2-) or methyl (-CH_3) groups within the hydrogel structure. Additionally, the peak at 1656 cm^{-1} is attributed to C=O stretching vibrations, indicating carbonyl groups from amides or carboxylic acids typically found in hydrogel backbones and crosslinkers. Moderate peaks at 1452 cm^{-1} and 1550 cm^{-1} correspond to C-H bending and N-H bending vibrations, respectively, which are characteristic of secondary amides, supporting the likelihood of amide connections within the hydrogel matrix. The peak at 1407 cm^{-1} may be associated with C-H bending in methylene groups or carboxylate ions, suggesting the presence of carboxylic acid components. Furthermore, a sharp peak at 1089 cm^{-1} reflects C-O stretching vibrations from ether or ester bonds, potentially originating from the polymer's structure or crosslinking agents. The peak at 1001 cm^{-1} represents C-O-C stretching, characteristic of glycosidic linkages in cellulose or synthetic polymers in the composite. These FTIR spectral analysis highlights a sophisticated hydrogel structure enriched with various functional groups and chemical interactions, which contribute to its exceptional water retention properties and broaden its potential applications. For example, the hydroxyl (-OH) groups enhance wettability, facilitating better electrolyte penetration and ion transport. Aliphatic hydrocarbons (-CH_2, -CH_3) contribute to structural integrity, ensuring mechanical stability during repeated charge-discharge cycles. Carbonyl (C=O) and oxygenated functional groups improve pseudocapacitive behaviour by participating in reversible redox reactions, thereby increasing charge storage capacity.

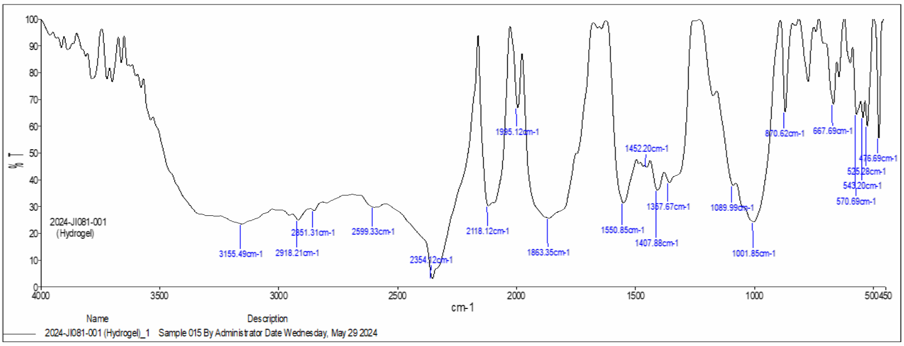


Fig. 1. FTIR analyses of the activated carbon composite.

As shown in Figure 2, the SEM images reveal a highly porous and irregular surface morphology, with micro- and mesopores measuring less than 200 nm, promoting ion diffusion and charge storage. Comparing SEM images of bamboo-based and other biomass-derived activated carbons would illustrate structural advantages and optimize material selection by providing insights into pore size distribution, surface roughness, and particle aggregation. Zhang et al. (2021) and Liu et al. (2020) have demonstrated that bamboo-based activated carbon exhibits a more interconnected pore structure compared to other biomass-derived materials, leading to superior electrochemical performance [16-17]. The hierarchical porous structure plays a crucial role in enhancing charge storage capacity and improving ion accessibility, making bamboo-based carbon a promising alternative for high-performance supercapacitors.

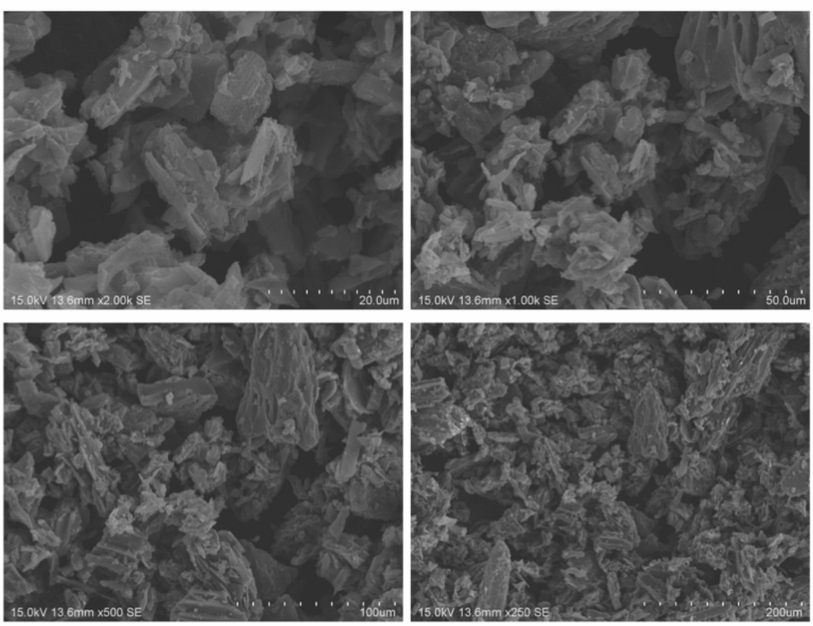
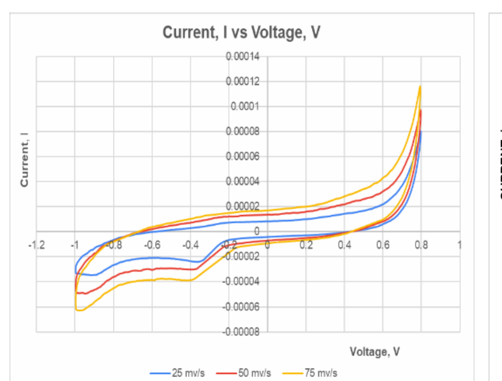


Fig. 2. SEM images of activated carbon composite a) x20 micrometers b) x50 micrometer c) x100 micrometer d) x200 micrometer.

3.2 Electrochemical Performance of Electrode

The cyclic voltamometry (CV) measurements were conducted, and the results are shown in Figure 3(a-c). The study demonstrates that the increasing KOH concentration enhances specific capacitance, with optimal performance recorded at 7% KOH concentration and 75 mV/s scan rate. As illustrated in Figure 3, the CV curves of the bamboo-based activated carbon electrode display a well-defined, symmetric leaf-shaped pattern with slightly broadened humps. This aligns with findings from previous studies, which indicate that higher electrolyte concentrations improve ionic conductivity [18]. According to Sun et al. (2019), increasing KOH concentration up to an optimal level improves the formation of micropores, enhancing electrochemical accessibility and increasing charge storage efficiency [19]. However, excessive KOH concentrations may lead to increased electrolyte viscosity, limiting ion diffusion and negatively impacting overall charge transfer kinetics [20]. Furthermore, studies by Chen et al. (2021) highlight that the scan rate plays a crucial role in determining supercapacitor performance, with higher scan rates leading to improved power density but potentially reducing charge storage efficiency due to incomplete ion diffusion [15]. For example, in Figure 3a, the peak at a scan rate of 75 mV/s is more pronounced than that at 25 mV/s. The minor humps observed in all the graphs suggest the occurrence of a subtle redox reaction within the voltage range of 0 to 0.5 V relative to the standard potential of Ag/AgCl [22].



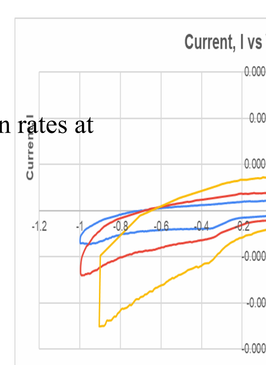


Fig. 3. CV curves of activated bamboo carbon electrode at different potential scan rates at different concentrations of KOH solution a) 3% b) 5% c) 7%.

4 Conclusion

In summary, the bamboo-based activated carbon electrode was successfully synthesized and comprehensively characterized for its morphology and structural properties using advanced analytical techniques such as SEM, FTIR, and XRD. SEM analysis revealed that the activated carbon composite possesses a rough and uneven surface with a diverse range of particle sizes, contributing to a high surface area that is advantageous for adsorption and catalysis applications. FTIR spectroscopy identified multiple functional groups, which suggested the presence of a complex hydrogel structure with hydrogen bonding, which enhances water retention and interaction capacities. XRD analysis further demonstrated a dual-phase structure comprising both crystalline and amorphous regions, providing an optimal balance of rigidity and elasticity for various applications. The electrochemical performance of the bamboo-based activated carbon electrodes showed that increasing the KOH concentration and scan rate significantly enhanced performance. The optimal results were achieved at a 7% KOH concentration and a 75 mV/s scan rate, leading to improved ionic conductivity, efficient charge transfer, high specific capacitance, stable charge-discharge behaviour, and excellent cyclic stability. These findings emphasize the potential of bamboo-based activated carbon as a sustainable and high-performance electrode material. This material holds great promise for advancing green energy storage technologies, offering a cost-effective and environmentally friendly solution for efficient energy storage systems.

Acknowledgment

This work was financially supported by the Ministry of Higher Education under Fundamental Research Grant Scheme (FRGS /1/2023/TK09/UPM/01/2) and and Putra Grant (Matching Grant/ 2023/9300494)

References

1. Benti, N. E., Gurmesa, G. S., Argaw, T., Aneseyee, A. B., Gunta, S., Kassahun, G. B., Aga, G. S., & Asfaw, A. A. Biotechol. for Bio., **14**(1)(2021).
2. Gautam, M., Patodia, T., Gupta, V., Sachdev, K., & Kushwaha, H.S. J. of Ener. Stor., **102**, 114088 (2024)
3. Lu,S .,Xiao,Q .,Yang,W .,Wang,X .,Guo,T .,Xie,Q .,& Ruan,Y. Intern. J. of Bio. Macromol.258, (2024).
4. Duan, Z., Wang, K., Cao, Y., Wang, J., & Liu, Q. Energ., 134171 (2024).
5. Sun,Z .,Li,L .,Wang,Z .,Gong,L .,& Sun,D. J. of Alloys and Comp.,939 (2023)
6. Goh, S.M.X., Chin, B.L.F., Huang, M.M., Yiin, C.L., Kurnia, J.C., Lam, S.S., Tan, Y.H., Chai, Y.H., & Rashidi, N.A. J. of Energ. Stor. **105**, (2025).
7. Zhang,Y ,.Yang,W ,.Fu,Q ,.Li,J ,.Zhu,X ,. & Liao,Q. Intern. J. of Hyd.Energ. **44,** 6 (2019)
8. Chonsakorn, S., Chombhuphan, R., Rattanaporn, K., Srivorradatphisan, S., Ruangnarong, C., & Khojitmate, S. Heliyon, **10,** 9 (2024).
9. Gao, Q., Huang, Y., Hu, J., Gan, J., & Yu, W. Intern. J. of Biol. Macromol., **279** (2024).
10. Gong,L., Zeng,R., Shi,Y., Yu,M., Yu,X., & Sun,D. Biores. Technol., **399** (2024).
11. Pan,K .,Ni,X .,Li,S .,Tian,Y .,& Xiong,Q. Dia.and Rel.Mat., **140** (2023).

12. Tang,X .,Song,H .,Liang,J .,Wu,M .,Zhang,Y .,Xie,Y .,Tang,Q ,.Qin,L ,. & Fan,X. Dia.and Rel.Mat. **151** (2025).
13. Long,J.W .,Bélanger,D .,Brousse,T ,Sugimoto,W .,Sassin,M.B .,& Crosnier,O. MRS Bulletin**, 36**, 7(2011).
14. Sharma,S .,& Chand,P. Res.in Chem., **5**(2023).
15. Chen, H., Hu, H., Han, F., Liu, J., Zhang, Y., & Zheng, Y. Dalt. Transac., **49,** 31 (2020).
16. Chen, X., Wang, Y & Liu, Jour. Of Ener. Stor, 35 (2021)
17. Liu et al. (2020)
18. Irkham,I.& Einaga,Y. The Analy.,**144**, 15(2019).
19. Sun, T. Chen, R and Zhou, Q, Carbon, 145 (2019)
20. Wang, H, Lu, C and Feng, J, Electrochemical Acta, 345 (2020).
21. Cougnon, C. Energ., **16**, 15 (2023).