

Morphological, Crystallinity, and Functional Group Analysis of Coconut Shell-Based Activated Carbon with Carbonization Temperature Variations for Supercapacitor Electrode Potential

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ABSTRACT

Supercapacitors are advanced energy storage devices with high power density and rapid charge-discharge capabilities. This study explores the potential of coconut shell-based activated carbon as an electrode material for supercapacitors. Coconut shell carbon powder was carbonized at temperatures ranging from 400°C to 700°C and chemically activated using 3M KOH for 24 hours. The activated carbon was then filtered, rinsed with distilled water until neutral pH, and dried at 120°C for 4 hours. Characterization was performed using Scanning Electron Microscopy (SEM), Brunauer-Emmett-Teller (BET) analysis, X-ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR). SEM images confirmed the formation of uniformly distributed pores, with higher carbonization temperatures leading to increased pore development. BET analysis showed that both surface area and pore volume increased with rising carbonization temperatures. XRD patterns revealed amorphous graphite-like carbon structures, with improved crystallinity at higher temperatures. FTIR spectra confirmed the presence of aromatic C=C and C-O functional groups. These results demonstrate that activated carbon derived from coconut shells exhibits favorable physicochemical properties, indicating strong potential as a low-cost and sustainable electrode material for supercapacitor applications.

1. Introduction

The decreasing availability of fossil fuels has prompted intensive research into alternative energy sources and environmentally friendly energy storage systems. Among various technologies, supercapacitors have emerged as promising energy storage devices due to their high power density, fast charging capability, and long cycle life with minimal environmental impact [1-2]. Compared to conventional capacitors, supercapacitors offer superior performance with capacitance values exceeding 100 F and rapid charging times within seconds [3-5]. Structurally, supercapacitors consist of two electrodes, an electrolyte, and a separator. The electrode plays a critical role as it directly interacts with the electrolyte, forming an electrical double layer for energy storage [6-8].

Carbon-based materials are widely used for electrode fabrication due to their excellent electrical conductivity, high surface area, chemical stability, and economic viability [9-11]. Activated carbon, in particular, is a preferred material owing to its highly porous structure, large surface area, good electrochemical characteristics, and natural abundance [12-15]. The porous nature of activated carbon facilitates efficient ion migration and adsorption at the electrode-electrolyte interface,

thereby enhancing the capacitance of the supercapacitor [8].

Coconut shells are considered a valuable precursor for activated carbon production due to their high lignocellulosic content, which can be effectively converted into carbon material through the carbonization process [16]. Their hard and dense structure, which is attributed to a high concentration of carbon and lignin as well as a low ash content, further enhances their suitability as a raw material for activated carbon [17]. Compared to other precursors, activated carbon derived from coconut shells exhibits superior characteristics, particularly in terms of well-developed porosity and high surface area, both of which contribute significantly to improving supercapacitor performance [12]. The high surface area and well-developed porosity of carbon materials can significantly enhance their electrical conductivity. The porous structure of activated carbon facilitates ion transport and adsorption, promoting electric double-layer formation at the electrode-electrolyte interface in electrochemical energy storage systems [8]. The porosity characteristics of carbon are influenced by various factors, including heat treatment conditions during both carbonization and activation processes [15][18].

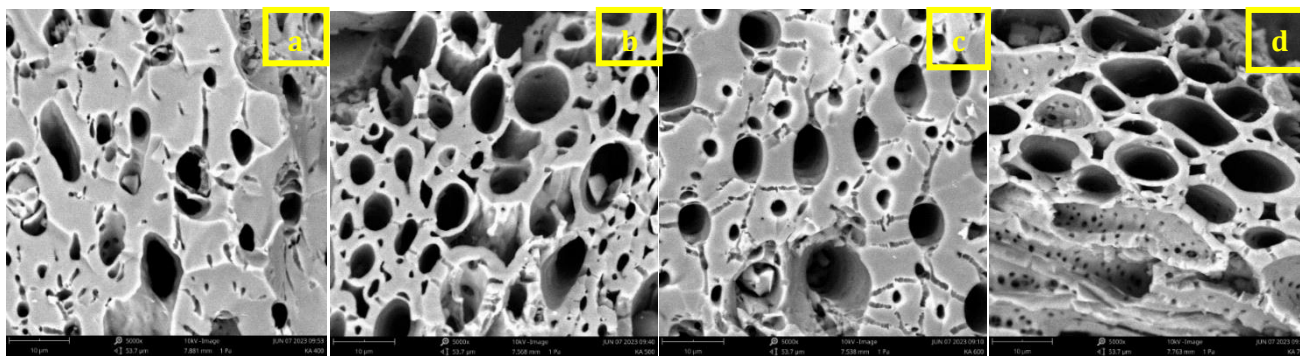


Fig. 1: Morphology of active carbon of coconut shell (a) KA400 (b) KA500 (c) KA600 and (d) KA700.

Moreover, the effectiveness of pore development in activated carbon is influenced not only by carbonization temperature but also by the type of chemical activator used. Potassium hydroxide (KOH) is widely recognized as an effective activating agent due to its strong basic nature, high reactivity, and ability to enhance porosity by removing impurities and expanding pore structures [19]. However, a systematic investigation of the effect of a wide carbonization temperature range (400°C–700°C) combined with chemical activation using 3M KOH remains limited in existing literature.

Therefore, this study introduces a novel approach by examining the simultaneous impact of both parameters on the physicochemical properties of activated carbon derived from coconut shells. Furthermore, the uniqueness of this study lies in its integrated use of SEM, BET, XRD, and FTIR analyses to investigate the material's morphology, porosity, crystallinity, and surface functional groups. In addition, the study includes a direct visual comparison of carbon samples with and without KOH activation, clearly demonstrating the crucial role of chemical activation in improving pore formation and surface cleanliness. Therefore, this research serves as a preliminary investigation into the potential of coconut shell-based activated carbon as an electrode material for supercapacitors, focusing on how different carbonization temperatures combined with KOH chemical activation affect the material's morphology, crystallinity, and surface chemistry. The findings are expected to provide valuable contributions to the development of cost-effective, sustainable, and high-performance biomass-derived electrode materials for future energy storage applications.

2. Methods

This study was carried out through several main stages, including material preparation, carbonization, grinding, chemical activation, and sample characterization. Coconut shells, as the raw material, were first cut into small pieces and cleaned to remove dirt and fiber. The shells were then sun-dried for three days until fully dry. The dried coconut shells were carbonized using a furnace at varying temperatures of 400°C–700°C for 2 hours. This process converts the organic material into carbon. The resulting carbon was crushed using a mortar and pestle to obtain a fine powder. The powder was then sieved using a 40mesh sieve to achieve uniform particle size.

To enhance the surface area, chemical activation was performed using a 3 M KOH solution with a mass

ratio of 1:1 between the carbon powder and the activating agent. The mixture was stirred at 80°C for 1 hour using a magnetic stirrer. It was then oven-heated at 130°C for 4 hours. After activation, the carbon was washed with distilled water until the pH was close to neutral (approximately 7). The final drying was conducted in an oven at 120°C for 4 hours [20]. The activated carbon samples were labeled as KA400, KA500, KA600, and KA700, where 'KA' stands for 'KOH-activated' and the numeric suffix indicates the carbonization temperature in degrees Celsius.

Characterization was conducted to analyze the physical and chemical properties of the activated carbon. Morphological analysis was carried out using Scanning Electron Microscopy (SEM), and surface area analysis was performed using the Brunauer–Emmett–Teller (BET) method. Crystalline structure was examined using X-Ray Diffraction (XRD), and functional group identification was done with Fourier Transform Infrared Spectroscopy (FTIR).

3. Experimental Result and Discussion

As shown in the Scanning Electron Microscopy (SEM) images in Fig. 1, all activated carbon samples derived from coconut shells and carbonized at temperatures between 400°C and 700°C exhibit a well-developed porous structure uniformly distributed across the surface. The formation of these pores is primarily attributed to the thermal decomposition of cellulose, hemicellulose, lignin, and volatile compounds present in the biomass. The release of these components during carbonization promotes the development of a porous morphology on the carbon surface [21]. The SEM analysis further reveals that increasing the carbonization temperature enhances the porosity of the carbon material. This is accompanied by significant morphological transformations, as indicated by increased surface roughness. These changes are likely due to intensified thermal degradation and the greater release of volatile substances at elevated temperatures, which results in the opening of previously blocked pores and the development of a more porous structure [16]. Moreover, a positive correlation is observed between carbonization temperature and pore formation, where higher temperatures lead to increased porosity, thereby improving the material's adsorption capacity [22]. Elevated temperatures also induce thermal cracking in the carbon matrix, which contributes to enhanced surface roughness, the formation of microporous structures, and an overall increase in total surface area [21].

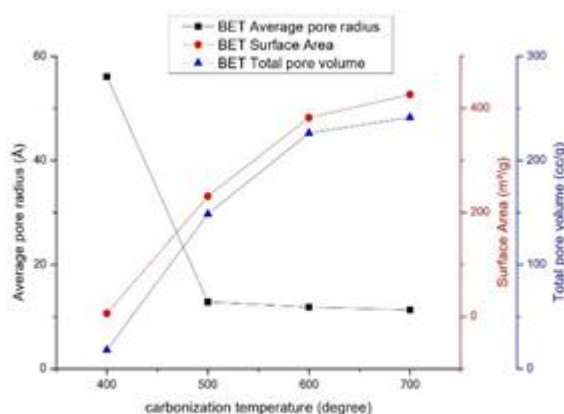


Fig. 2: average pore, total pore volume and surface area of active carbon coconut shell.

These morphological observations are further supported by the Brunauer–Emmett–Teller (BET) analysis, as shown in Fig. 2. The results indicate that both the specific surface area and total pore volume increase with rising carbonization temperatures. In particular, the sample carbonized at 700°C exhibited the highest surface area and pore volume, along with the smallest average pore diameter. This trend suggests that greater combustion intensity promotes the formation of micropores. The increased pore volume at higher temperatures reflects an enhanced adsorption capacity, as more gas molecules are retained within the porous structure. In addition, the formation of more uniform internal microstructures at elevated temperatures may slow the gasification rate within the particle core, further promoting the development of numerous fine micropores [23]. These findings confirm that higher carbonization temperatures result in smaller average pore diameters, while simultaneously increasing total pore volume and specific surface area.

Conversely, at carbonization temperatures below 700°C, both the specific surface area and pore volume are lower. This is primarily due to incomplete decomposition of volatile compounds, which remain as residues (tar) on the carbon surface. These residues block existing pores and hinder the formation of new ones, thereby limiting overall porosity and reducing the accessible surface area [24]. Pore formation is a critical factor in enhancing the specific surface area of activated carbon, which is essential for improving its performance in electrochemical applications. The presence of a well-developed porous structure facilitates the movement of electrolyte ions within the electrode material, thereby reducing ion diffusion resistance and improving charge transport efficiency [16]. Pore formation is very important for ion migration. It is also important for ions to occupy all the pores of the carbon repeatedly forming a layer at the electrode-electrolyte interface. Therefore, the accumulation of ions during charging will increase, thereby increasing the specific capacitance of the material [8][25]. A greater number of pores results in a larger surface area available for the attachment of functional groups, thus improving the adsorption properties of the carbon material [26].

The formation of pores in activated carbon derived from coconut shell is influenced not only by the carbonization temperature but also by the presence of a chemical activator such as potassium hydroxide (KOH). As shown in Fig. 3, the morphology of carbonized coconut shell at 400°C without the

addition of KOH reveals that pores have begun to

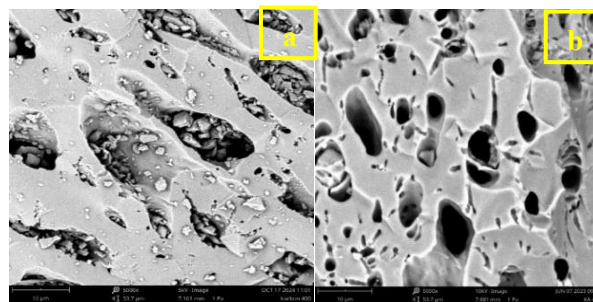


Fig. 3: Scanning Electron Microscope (SEM) results of coconut shell carbonized at 400°C: (a) without activation, (b) with KOH activation.

form, but many remain blocked by impurities. The presence of these impurities can hinder the adsorption and diffusion of electrolyte ions into the electrode material, thereby reducing its electrochemical performance [27].

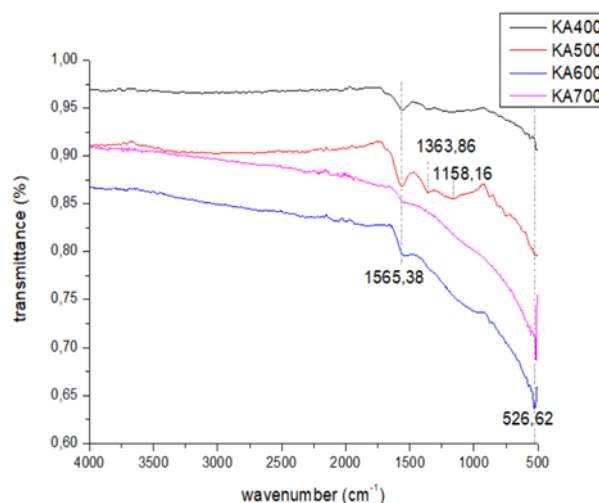


Fig. 4: FTIR spectrum of active carbon coconut shell.

In contrast, the carbon sample treated with KOH at the same carbonization temperature (400°C) exhibits a significantly more porous and cleaner surface morphology. This improvement is attributed to the chemical action of KOH, which effectively decomposes and removes surface impurities during the activation process. Additionally, the evaporation of KOH during carbonization may contribute to pore formation by leaving behind voids in the carbon structure, thus enhancing porosity [28].

Fourier Transform Infrared (FTIR) spectroscopy analysis, as presented in Fig. 4, reveals a consistent absorption peak at 1565.38 cm⁻¹, which falls within the characteristic range of 1475–1600 cm⁻¹. This peak is attributed to the stretching vibrations of aromatic C=C bonds, indicating the presence of aromatic ring structures originating from lignin retained in the activated carbon [29]. Similar peaks have been reported in previous studies, such as at 1599.02 cm⁻¹, further confirming the presence of these aromatic functional groups [16][27]. Additionally, an absorption peak observed at 526.62 cm⁻¹ lies within the fingerprint region (500–1500 cm⁻¹), which is known for its complex absorbance pattern due to the bending vibrations of various molecular bonds [30].

In the KA400 and KA500 samples, weak absorption bands appear at 1363 cm⁻¹ and 1158.16 cm⁻¹. The band around 1363 cm⁻¹ is commonly associated with structural disorder in graphite-like

carbon systems [31]. while the peak near 1158.16 cm^{-1} corresponds to C–O stretching vibrations, typically observed within the 1000–1300 cm^{-1} region [29]. These findings are in agreement with previous reports that detected similar peaks around 1150 cm^{-1} [16][27]. The emergence of the C–O peak can be explained by the increased reduced mass of the bonded atoms, which shifts the vibration frequency to lower wavenumbers [29]. This C–O stretching band is often linked to residual cellulose, suggesting that at carbonization temperatures below 500°C, cellulose decomposition is incomplete. In contrast, the absence of the C–O peak at 600°C and above implies the complete decomposition of cellulose, with lignin being the predominant remaining component [10][32]. The presence of aromatic (C=C) and carbonyl (C=O) functional groups is particularly beneficial for supercapacitor applications. These groups enhance surface wettability and contribute to faradaic redox reactions, thereby improving the specific capacitance of the electrode material [10].

X-ray Diffraction (XRD) analysis was carried out to evaluate the structural transformation and crystallinity of the activated carbon as a function of carbonization temperature. Fig. 5 presents the XRD patterns of samples KA400 through KA700. All samples exhibit a broad diffraction peak in the range of $2\theta = 24^\circ\text{--}25^\circ$, corresponding to the (002) plane, and a weaker peak at $2\theta = 43^\circ\text{--}45^\circ$, which is attributed to the (100) plane. These peaks are characteristic of graphite-like carbon structures [16] [9]. The broadening of the (002) peak suggests the presence of disordered carbon or an amorphous structure. A wide diffraction signal in the range of $2\theta = 20^\circ\text{--}30^\circ$ typically indicates a poorly ordered arrangement of carbon layers, often resulting from incomplete graphitization. This structure is known to enhance the adsorption capacity of the carbon material due to its open and disordered nature [14]. Moreover, the broad peak can also be associated with the transition from a non-graphitic polymer to a partially graphitized carbon framework [9].

The thermal decomposition behavior of the major constituents of coconut shell, namely hemicellulose, cellulose, and lignin, occurs over different temperature ranges. Since not all of these components decompose completely at lower carbonization temperatures, the crystallinity of the resulting carbon remains low. In particular, the presence of residual lignin contributes significantly to the predominance of the amorphous phase in the carbon matrix at these temperatures [21].

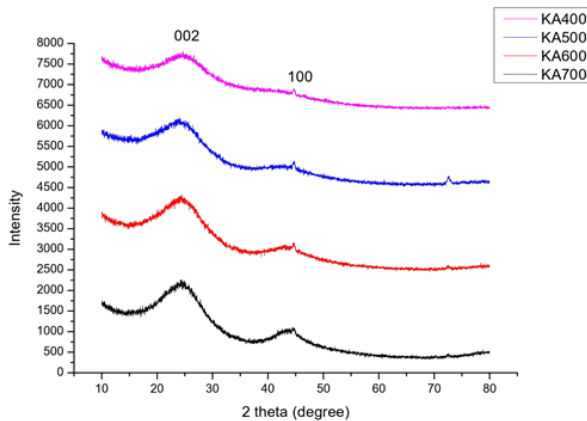


Fig. 5: XRD pattern of active carbon coconut shell.

Table 1: Crystallinity of Coconut Shell Activated Carbon Variation of Carbonization Temperature

Sample	2 θ	FWHM	Total Area of Crystalline Peak	% Index Crystallinity
KA400	24,73	13,53	15928,69	50,19
	44,67	0,84	980,74	
KA500	24,03	12,02	17321,3	52,31
	44,73	4,53	2545,34	
KA600	24,47	11,94	19012,52	55,86
	44,71	6,85	4033,77	
KA700	24,19	13,51	19208,51	58,99
	44,47	8,08	5053,26	

As summarized in Table 1, increasing the carbonization temperature leads to an observable increase in crystallinity. At 400°C, the sample already begins to exhibit a graphite-like structure with a crystallinity index of approximately 50.19%. This index gradually increases with temperature, reaching a maximum of 58.99% at 700°C. The rise in crystallinity is also accompanied by an increase in peak intensity and sharper peak profiles, which indicates greater structural ordering and the progressive development of graphitic domains [9]. The (100) diffraction peaks, found in the 2θ range of $40^\circ\text{--}50^\circ$, also show increased intensity and Full Width at Half Maximum (FWHM) values as the carbonization temperature rises. This suggests that structural rearrangement is taking place in the amorphous regions, supporting the formation of more defined crystallite domains within the carbon material [21].

The enhancement in crystallinity with rising temperature can be attributed to the greater availability of thermal energy, which facilitates bond breaking and reformation during carbonization. This energy drives further structural rearrangements, promoting the conversion of amorphous carbon into a more ordered, graphite-like structure [9][21]. In particular, the presence of cellulose, which naturally exhibits a crystalline structure, may contribute to this transformation when subjected to sufficient heat treatment. Such crystallinity is advantageous in activated carbon production, as it is generally associated with improved stability and conductivity, both of which are desirable for electrochemical applications [33].

4. Conclusion

This study demonstrates that coconut shell is a highly promising precursor for the production of activated carbon due to its high lignocellulosic content, low ash level, and favorable carbon structure. The variation in carbonization temperatures (400°C to 700°C), combined with chemical activation using KOH, significantly influences the physicochemical properties of the resulting activated carbon. The morphological analysis via SEM confirms that increasing the carbonization temperature enhances surface roughness and promotes the development of a well-distributed porous structure. This structural evolution is attributed to the thermal degradation and release of volatile compounds, which open blocked pores and improve ion transport pathways.

The BET analysis further supports this by showing a direct relationship between higher carbonization temperatures and increased surface area and pore volume, while simultaneously reducing average pore diameter, ideal characteristics for supercapacitor electrode applications.

FTIR analysis identifies the presence of functional groups such as aromatic C=C and carbonyl C=O, which are beneficial for electrochemical performance as they enhance surface wettability and participate in faradaic reactions. These groups are especially dominant at lower carbonization temperatures, indicating partial decomposition of cellulose, whereas their absence at higher temperatures suggests complete cellulose breakdown, leaving lignin as the main structural component.

XRD analysis reveals that carbon materials produced at higher carbonization temperatures exhibit increased crystallinity. The growth of graphite-like domains at elevated temperatures is driven by greater thermal energy availability, which supports bond reformation and structural ordering. A crystallinity index of 58.99% was achieved at 700°C, indicating significant transformation from amorphous to semi-crystalline carbon.

Overall, the combination of high surface area, well-developed porosity, appropriate surface functional groups, and improved crystallinity makes coconut shell-based activated carbon a highly effective and sustainable electrode material for supercapacitor applications. Optimizing carbonization temperature is crucial to tailoring the structural and electrochemical characteristics of the carbon for maximum performance.

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