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Morphological and Textural Characterization of Activated Carbon Derived from Microwave-Assisted KOH Activation of Banana Peels

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Abstract

Banana peel biomass was converted into activated carbon through microwave-assisted KOH activation at a constant microwave power of 800 W and a KOH/precursor mass ratio of 1:1, using activation times of 10, 20, 30, and 40 min. The influence of activation time on the morphological and textural properties of the resulting activated carbons was systematically investigated using field emission scanning electron microscopy (FESEM) and nitrogen adsorption–desorption (BET) analyses. FESEM observations revealed progressive pore development and increased surface roughness with prolonged activation, reflecting the enhanced etching effect of KOH. Samples activated for 10–20 min retained fibrous plant-cell features and exhibited predominantly microporous structures, with a maximum BET surface area of 316 $m^2 g^{-1}$ at 20 min. Extending the activation time to 30–40 min further enhanced pore development, increasing the specific surface area to 471 $m^2 g^{-1}$ while reducing the average pore diameter from 2.86 to 1.90 nm. These changes indicate progressive pore refinement and the formation of a well-developed microporous network. The results demonstrate that microwave-assisted KOH activation provides a rapid and energy-efficient approach for producing porous activated carbon from banana peel biomass, with activation time serving as a key parameter for tailoring pore characteristics and surface area for potential environmental remediation and energy-storage applications.

Keywords: Activated carbon; banana peel biomass; microwave-assisted activation; FESEM; BET analysis; microporous carbon; pore architecture.

I. Introduction

Activated carbon (AC) is a highly porous carbonaceous material characterized by an extensive internal surface area and excellent adsorption capacity, making it one of the most widely used porous materials for environmental and industrial applications [1]. Owing to its favorable physical and chemical properties, activated carbon has been extensively employed for the removal of volatile organic compounds (VOCs), heavy metals, dyes, and pharmaceutical contaminants from air and water [2-3]. Beyond environmental remediation, its high surface area, tunable pore structure, and good electrical conductivity have also enabled its application as an electrode material in electrochemical energy storage

devices, including supercapacitors and batteries [4–6]. The performance of activated carbon is primarily governed by its textural characteristics, particularly the specific surface area, pore volume, pore size distribution, and surface chemistry [7].

The conversion of agricultural waste into activated carbon has attracted considerable attention as a sustainable and cost-effective alternative to conventional coal- and petroleum-derived precursors. Among the numerous biomass resources investigated, banana peels (Musa spp.) have emerged as a promising precursor because of their high cellulose and hemicellulose contents, low cost, and widespread availability as an agricultural by-product [8]. Activated carbon produced from banana peels has demonstrated favorable porosity and specific surface area, making it suitable for applications such as carbon dioxide capture, wastewater treatment, and the adsorption of a wide range of environmental contaminants [9].

Chemical activation using potassium hydroxide (KOH) is widely recognized as one of the most effective approaches for producing highly microporous activated carbons. During activation, KOH promotes dehydration of the carbonaceous precursor, followed by reactions that generate potassium carbonate and metallic potassium. These reactions facilitate carbon etching, intercalation between graphitic layers, and the development of an interconnected pore network, ultimately enhancing both porosity and specific surface area [6], [10].

Microwave-assisted activation has emerged as an attractive alternative to conventional thermal activation because it provides rapid and volumetric heating, significantly reducing processing time and energy consumption. When combined with KOH activation, microwave heating accelerates pore development and produces activated carbons with high specific surface areas and well-defined pore structures within considerably shorter processing times than conventional furnace-based methods [11-12].

Among the processing parameters governing microwave-assisted activation, activation time plays a critical role in determining the final morphology and pore architecture of the resulting activated carbon. Insufficient activation time limits pore formation, whereas excessive exposure may cause over-etching, pore widening, or structural collapse, thereby reducing the accessible surface area [13]. Although microwave-assisted KOH activation of biomass-derived carbons has been widely investigated, systematic studies focusing on the influence of activation time on the morphological evolution and textural characteristics of banana peel-derived activated carbon remain limited. Therefore, this study systematically investigates the effect of microwave activation time on the morphology and pore structure of banana peel-derived activated carbon using field emission scanning electron microscopy (FESEM) and nitrogen adsorption–desorption (BET) analyses. The findings provide insights into optimizing microwave activation conditions for the production of high-performance porous carbons from sustainable biomass resources.

II. Materials and Methods

A. Materials

Fresh banana peels (Musa spp.) were collected from local fruit vendors in Kaduna, Nigeria, and used as the carbon precursor. The peels were thoroughly washed with distilled water to remove adhering impurities, drained, cut into small pieces, and dried in a microwave oven operating at 400 W for 45 min. The drying process was repeated until a constant mass was achieved. A total of 200 g of dried biomass was subsequently carbonized under a limited oxygen atmosphere in a microwave oven at 800 W for 2 hours, yielding 89.2 g of carbonized material. The carbonized product was ground and sieved to obtain particles smaller than 250 μm.

Analytical-grade potassium hydroxide (KOH), hydrochloric acid (0.1 M HCl, Sigma-Aldrich, Burlington, MA, USA), and distilled water were used throughout the study without further purification.

B. Preparation of Activated Carbon

The carbonized banana peel powder was impregnated with saturated KOH solution at a precursor-to-KOH mass ratio of 1:1 and stirred continuously for 6 hours to ensure uniform impregnation. The mixture was subsequently dried at 115 °C before microwave activation.

Microwave activation was carried out at a constant power of 800 W under a nitrogen atmosphere for activation times of 10, 20, 30, and 40 min. After cooling to room temperature, the activated products were washed with 0.1 M HCl to remove residual inorganic species, followed by repeated washing with distilled water until the filtrate reached approximately neutral pH (≈7). The samples were then dried at 115 °C for 12 h and stored in a desiccator before characterization. The resulting activated carbons are hereafter referred to as banana peel-derived activated carbon (BPAC).

C. Characterization

The surface morphology of the prepared samples was examined using field emission scanning electron microscopy (FESEM). Before imaging, the samples were mounted on aluminum stubs using conductive carbon tape and sputter-coated with a thin layer of gold to improve electrical conductivity. Micrographs were acquired at different magnifications to evaluate the evolution of the pore structure.

The textural properties were determined by nitrogen adsorption–desorption measurements using a BET surface area analyzer. Before analysis, the samples were degassed at 300 °C for 3 hours to remove physically adsorbed moisture and volatile species. Nitrogen adsorption measurements were performed at 77 K (−196 °C), and the specific surface area (SBET) was calculated using the Brunauer–Emmett–Teller (BET) method. The total pore volume (V_t) was estimated from the amount of nitrogen adsorbed at a relative pressure of P/P_0 = 0.99. Micropore volume was determined using the t-plot method, whereas mesopore volume and pore size distribution were calculated using the Barrett–Joyner–Halenda (BJH)

method.

III. Results and Discussion

A. SEM Analysis

Fig. 1 presents FESEM micrographs of the carbonized banana peel and the KOH-activated samples prepared at different microwave activation times. Images (a–c) correspond to the carbonized sample without chemical activation, while images (d–f), (g–i), (j–l), and (m–o) represent samples activated with KOH for 10, 20, 30, and 40 min, respectively.

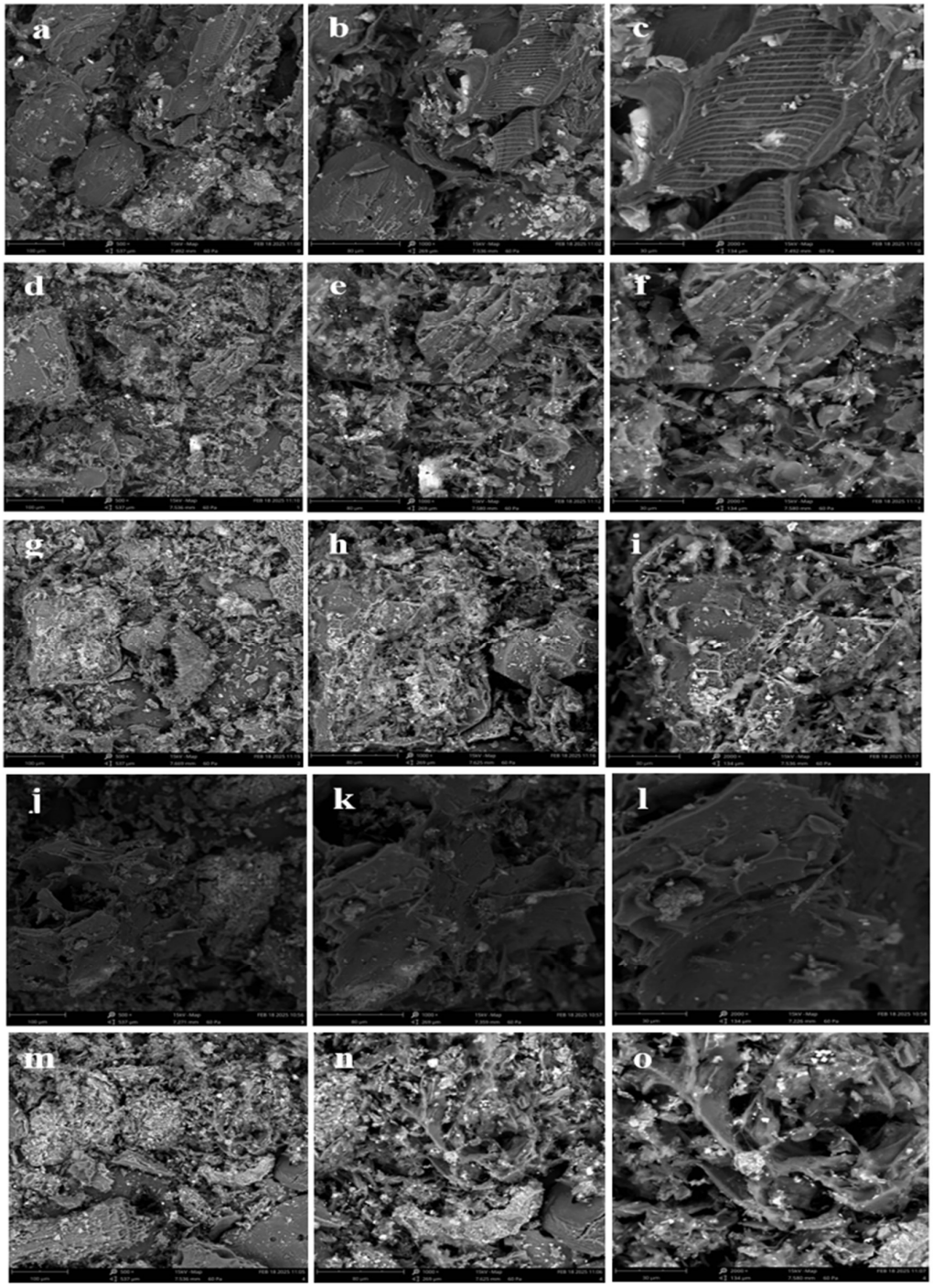

Fig. 1. SEM images of Carbonized Banana Peel (a–c) and BPAC activated at 10 min (d–f), 20 min (g–i), 30 min (j–l), and 40 min (m–o) at 800 W, at different magnifications.

The carbonized sample exhibits a rough and heterogeneous surface characterized by irregular ridges, fissures, and relatively few visible pores. These morphological features result from the thermal decomposition of cellulose, hemicellulose, and lignin during carbonization, accompanied by the evolution of volatile species that leave behind initial pore cavities [15], [17-18]. In addition, cracks and fissures associated with thermal shrinkage [19], fused carbon aggregates [20], and bright regions attributed to residual inorganic mineral species, including potassium and calcium oxides [21], are evident in the carbonized material.

Following KOH activation, the surface morphology changed markedly, exhibiting a significantly higher density of pores and increased surface roughness. The enhanced porosity is attributed to the chemical reactions between KOH and the carbon matrix, which promote carbon etching and the development of interconnected micro- and mesoporous structures [4]. Samples activated for 10 and 20 min retained portions of the original fibrous plant-cell morphology while showing the formation of numerous micropores. As the activation time increased to 30 and 40 min, the pore network became more extensive and uniformly distributed, indicating progressive development of the porous structure.

The observed morphological evolution is consistent with the established mechanism of KOH activation. During microwave heating, potassium species intercalate into the carbon framework while simultaneous gasification reactions remove carbon atoms, creating new pores and enlarging existing ones [10], [18]. The rapid volumetric heating characteristic of microwave irradiation further promotes uniform activation throughout the precursor, resulting in a well-developed pore network suitable for adsorption, energy storage, and catalytic applications [17], [20]. These observations agree with the BET results, which demonstrate a corresponding increase in specific surface area and pore volume with increasing activation time.

Overall, the FESEM analysis confirms that microwave-assisted KOH activation effectively transforms carbonized banana peel into a highly porous activated carbon. The progressive increase in pore development with activation time highlights the critical role of microwave-assisted chemical activation in tailoring the morphology and textural properties of biomass-derived activated carbons.

B. BET and Pore Structure Analysis

Fig. 2 presents the Dubinin–Astakhov (DA) pore size distribution curves for the carbonized banana peel and the KOH-activated samples prepared at different microwave activation times. The corresponding pore volume and average pore diameter values are summarized in Table 1.

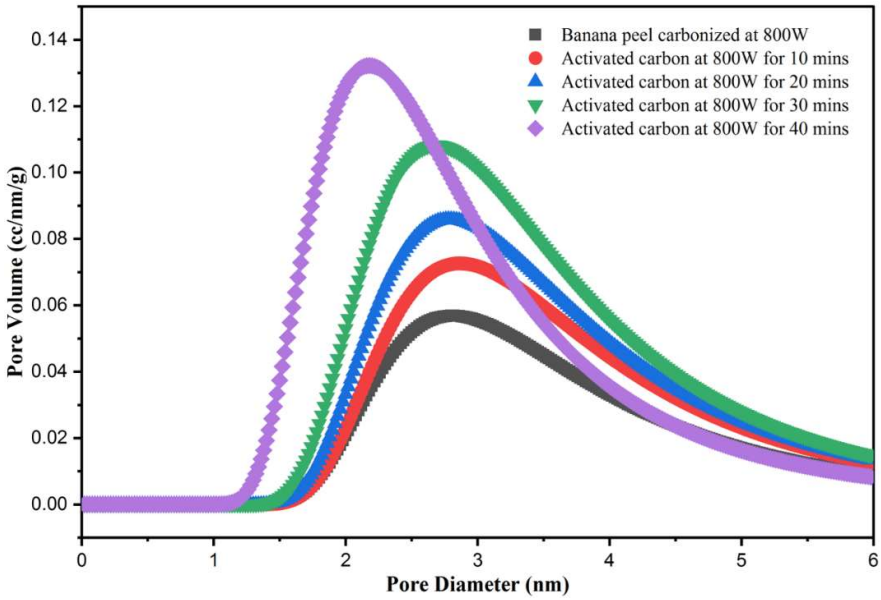

Fig. 2 .DA curve showing pore volume distribution for Carbonized and BPAC at 10, 20, 30, and 40 minutes activation time at 800 W.

Table I. Calculated pore volume and pore diameter for Carbonized and BPAC.

Sample	Microwave power (W)	Time (mins)	Pore Vol. (cc/g)	Pore Diameter (nm)
Carbonized Banana Peel	800	0	0.056	2.82
Activated carbon	800	10	0.060	2.86
Activated carbon	800	20	0.080	2.78
Activated carbon	800	30	0.100	2.68
Activated carbon	800	40	0.120	1.90

The carbonized sample exhibited the lowest pore volume (0.056 $cm^3\ g^{-1}$) with an average pore diameter of 2.82 nm, indicating that carbonization alone generated only a limited porous structure, which is characteristic of biomass-derived carbons before chemical activation [4]. Upon microwave-assisted KOH activation, progressive pore development was observed with increasing activation time. At 10 min, the pore volume increased slightly to 0.060 $cm^3\ g^{-1}$, reflecting the initial formation of pores as KOH began to react with and etch the carbon framework [22]. Extending the activation time to 20 min further increased the pore volume to 0.080 $cm^3\ g^{-1}$ while reducing the average pore diameter to 2.78 nm, indicating continued pore development through prolonged interaction between KOH and the carbon matrix [23].

Further activation for 30 min resulted in a pore volume of 0.100 $cm^3\ g^{-1}$ and a reduction in average pore diameter to 2.68 nm, suggesting the development of a more interconnected porous structure [21]. The sample activated for 40 min exhibited the highest pore volume (0.120 $cm^3\ g^{-1}$) and the smallest average pore diameter (1.90 nm), demonstrating that prolonged microwave activation promoted extensive pore formation and refinement, leading to a well-developed porous network [24]. The progressive increase in pore volume accompanied by decreasing pore diameter indicates that microwave-assisted KOH activation effectively enhanced pore generation while refining the pore architecture.

The increase in pore volume is directly associated with the development of accessible internal surface area, thereby providing a greater number of adsorption sites. Meanwhile, the reduction in pore diameter enhances surface accessibility and may improve adsorption efficiency and electrochemical charge storage by increasing the interaction between the porous carbon and adsorbate or electrolyte species. However, excessively narrow pores may restrict mass transport and ion diffusion, particularly in electrochemical applications [25].

The Brunauer–Emmett–Teller (BET) method is the most widely employed approach for determining the specific surface area of porous materials from nitrogen adsorption–desorption isotherms at 77 K. Unlike the Langmuir model, the BET theory accounts for multilayer adsorption and therefore provides a more realistic description of gas adsorption on heterogeneous porous surfaces [26]. The specific surface area was calculated from the BET equation using the monolayer adsorption capacity obtained from the linear region of the adsorption isotherm.

$$\frac{P}{V(P^0-P)} = \frac{1}{V_m} + \frac{c-1}{V_m}\frac{P}{P^0} \quad (1)$$

$$c = \exp\left[\frac{\Delta H_A - \Delta H_L}{RT}\right] \quad (2)$$

Where V_m is the monolayer capacity, P_0 is the saturation vapor pressure, and P is the gas pressure, while c relates to the heat of first layer adsorption (ΔH_A), heat of liquefaction (ΔH_L), temperature T, and gas constant R.

Fig. 3 presents the BET plots for the carbonized and activated samples, while the calculated specific surface areas are summarized in Table II.

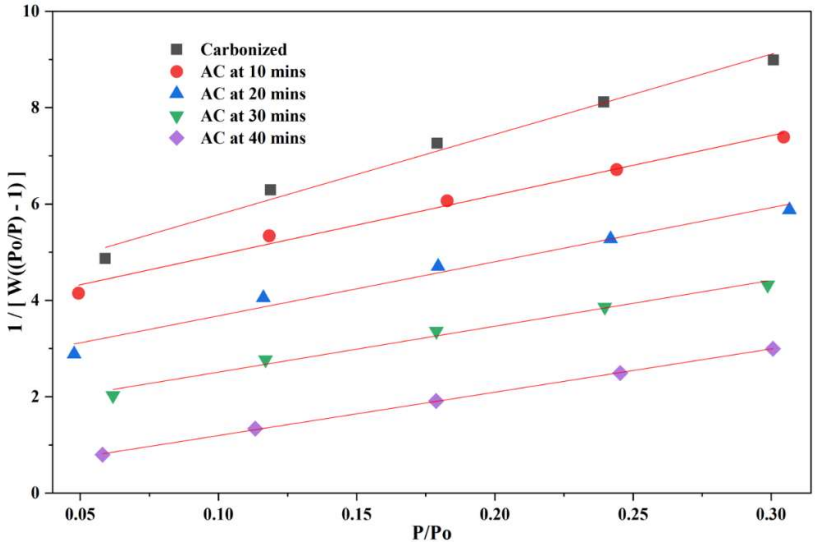

Fig. 3.BET linear plot for Carbonized and BPAC at 10, 20, 30, and 40 minutes activation time at 800 W.

Table II. BET specific surface area of carbonized banana peel and BPAC samples.

Sample	Microwave power (W)	Time (mins)	Pore Vol. (cc/g)	Pore Diameter (nm)
Carbonized Banana Peel	800	0	0.056	2.82
Activated carbon	800	10	0.060	2.86
Activated carbon	800	20	0.080	2.78
Activated carbon	800	30	0.100	2.68
Activated carbon	800	40	0.120	1.90

The carbonized sample exhibited a specific surface area of 210 $m^2 g^{-1}$. Following microwave-assisted KOH activation, the BET surface area increased progressively with activation time, reaching 271, 316, 394, and 471 $m^2 g^{-1}$ for activation times of 10, 20, 30, and 40 min, respectively. This steady increase demonstrates that prolonged microwave exposure promoted continuous pore development through enhanced chemical activation of the carbon matrix [27].

The increase in surface area can be attributed to the combined effects of microwave heating and KOH activation. Rapid volumetric heating accelerates the decomposition of residual organic matter and facilitates the intercalation of potassium species into the carbon framework. Simultaneously, gasification reactions remove carbon atoms from the matrix, creating new pores while enlarging existing ones, thereby increasing the accessible surface area [6,10]. The final BET surface area of 471 $m^2 g^{-1}$ represents a 124% increase relative to the carbonized sample and falls within the range commonly reported for KOH-activated biomass-derived carbons (approximately 400–600 $m^2 g^{-1}$) [4]. This substantial enhancement confirms that activation time is a critical parameter governing pore development and the textural properties of microwave-assisted activated carbons.

The BET results are in excellent agreement with the FESEM observations, which revealed progressively rougher surfaces and increased pore density with increasing activation time. Together, these findings demonstrate that microwave-assisted KOH activation effectively transforms carbonized banana peel into a highly porous activated carbon with significantly improved surface characteristics suitable for adsorption, catalysis, and energy-storage applications.

IV. Conclusion

The influence of microwave activation time on the morphological and textural properties of KOH-activated carbon derived from banana peel biomass was systematically investigated. FESEM analysis revealed progressive development of a porous structure with increasing activation time, while BET characterization confirmed a corresponding increase in specific surface area and pore volume. The BET surface area increased from 210 $m^2 g^{-1}$ for the carbonized sample to 471 $m^2 g^{-1}$ after 40 min of microwave activation, representing an improvement of approximately 124%. Simultaneously, the average pore diameter decreased, indicating progressive pore refinement and the development of a well-defined porous network. Among the activation conditions investigated, 30–40 min produced activated carbons with the most favorable textural characteristics, including the highest specific surface area and enhanced pore development.

These findings demonstrate that microwave-assisted KOH activation is an effective and energy-efficient approach for converting banana peel biomass into high-surface-area activated carbon. The study further establishes activation time as a key parameter governing pore evolution and surface characteristics, providing useful guidance for optimizing biomass-derived activated carbons for potential applications in adsorption, catalysis, and electrochemical energy-storage systems.

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Conflicts of Interest

The authors declare no conflicts of interest.

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