THE EFFECT OF VARIATIONS IN ACTIVATOR CONCENTRATION AND ACTIVATION TIME ON THE QUALITY OF ACTIVATED CARBON BASED ON BANANA STEMS

Nadia Febriana*, Lalu Ahmad Didik Meiliyadi, Kurniawan Arizona
Departement of Physics Education, Faculty of Education and Teacher Training, Universitas Islam Negeri Mataram, Jl. Gajah Mada No. 100, Mataram, 83116, Indonesia
*email: 220108004.mhs@uinmataram.ac.id

ABSTRACT

This study aims to synthesize banana stem-based activated carbon through chemical activation using HCl and NaOH at concentrations of 0.5 M and 1 M and activation times of 2 and 4 hours. FT-IR spectra identified –OH, C=O, aromatic C=C, and C–O functional groups in all samples, indicating the potential of banana stems as a raw material for activated carbon, with HCl activation yielding more optimal characteristics. SEM characterization showed that increasing the concentration and activation time resulted in a more porous structure with particle sizes of 0.98–1.63 µm, with the smallest size obtained using 1 M HCl for 4 hours. EDX analysis revealed a dominance of C and O elements, with the highest carbon content of 52.71% (atomic) in 1 M HCl. Moisture content ranged from 1.68–3.13% and met SNI No. 06-3730-1995. Ash content in the HCl treatment was 10%, meeting the standard, while in the NaOH treatment it was 20%. The Pb adsorption test showed the highest efficiency in 1 M HCl at 72.50%, higher than that of NaOH, which decreased to 49.00%.

Keywords: *Activated carbon; Banana stems; Chemical activation; Material characterization*

INTRODUCTION

Increased industrial and domestic activity in recent decades has led to increased environmental pollution, particularly water pollution caused by liquid waste containing organic and inorganic substances, as well as heavy metals (Oko et al., 2021). One method that is widely used to overcome this problem is adsorption, because it is considered effective, simple, and relatively inexpensive (Purwanti et al., 2021). The success of the adsorption process is greatly influenced by the quality of the adsorbent used, with activated carbon being the most commonly used material due to its large surface area, high porosity, and good adsorption capacity for various types of pollutants (Hidayah & Rosariawari, 2024; Sibarani et al., 2022; Suastika et al., 2023).

Activated carbon can be made from various raw materials containing carbon, both from fossil sources and biomass (Febrianti et al., 2023). In an effort to support the concept of sustainability and waste management, the use of natural materials and biomass waste as raw materials for activated carbon has become a major concern(Mustafa et al., 2023; Sirajuddin & Atasa, 2023). Agricultural waste, especially that with high cellulose, hemicellulose, and lignin content, has great potential to be converted into activated carbon with competitive and environmentally friendly characteristics (Sirajuddin & C, 2023; Suherman et al., 2021).

Banana stems are one of the abundant agricultural wastes in Indonesia that have not been optimally utilized (Aisyi & Putra, 2023). The complex organic compounds contained in banana stem make them a potential raw material for the production of activated carbon (Putri et al., 2022; Suliestyah et al., 2023). The use of banana stem as activated carbon not only contributes to waste reduction, but also has the potential to produce an economical and readily available alternative adsorbent for various purification and environmental treatment applications (Nugraha et al., 2022; Sholikhah et al., 2021).

The quality of activated carbon is greatly influenced by the activation process, both physically and chemically (Saban et al., 2023; Tarmidzi et al., 2021). Important parameters in the chemical activation process include the type and concentration of the activator and the activation time. Variations in activator concentration and activation time will affect pore formation, specific surface area, and the absorptive capacity of activated carbon (Darajat et al., 2023; Muhajir et al., 2021). Therefore, proper activation parameter settings are key factors in producing activated carbon with optimal quality that meets established standards (Ihsan et al., 2023; Prayogatama et al., 2022).

Previous studies have shown the success of producing activated carbon from various natural materials (Imani et al., 2021). Research by Nindhytia

Anandy Berliany et al. (2023) reports that activated carbon made from peanut shells used as a phosphate adsorbent in laundry waste experienced an increase in iodine adsorption capacity after the activation process, indicating an improvement in the quality of the activated carbon (Berliany et al., 2023). In addition, Khalimatus Sa'diyah et al. (2021) successfully utilized sawdust as activated carbon that is effective in absorbing pollutants and heavy metals, demonstrating the potential of wood biomass as a source of activated carbon (Sa'diyah et al., 2021). Another study by Arif Nurrahman et al. (2021) revealed that lignite coal-based activated carbon meets SNI standards and has great potential for application in various industrial sectors (Nurrahman et al., 2021). However, research on activated carbon based on banana stem with varying concentrations and activation times has not yet been conducted.

Therefore, this study was conducted to examine the effect of variations in activator concentration and activation time on the quality of banana stem-based activated carbon. The results of this study are expected to determine the optimal activation conditions to produce high-quality activated carbon that meets applicable quality standards. In addition, this study is also expected to contribute scientifically to the development of biomass-based activated carbon and support the use of agricultural waste as an environmentally friendly and sustainable alternative adsorbent.

METHOD

The research method used was the experimental method, which aims to determine the effect of a treatment on the observed variable through the application of controlled treatments. In this study, variations in activator concentration and activation time were used as independent variables, while the quality of banana stem-based activated carbon was used as the dependent variable. This method allows for objective analysis of cause-and-effect relationships and produces accurate data on the effectiveness of the treatment in improving the quality of activated carbon. This research was conducted in the Laboratory Universitas Islam Negeri Mataram (Meiliyadi et al., 2022).

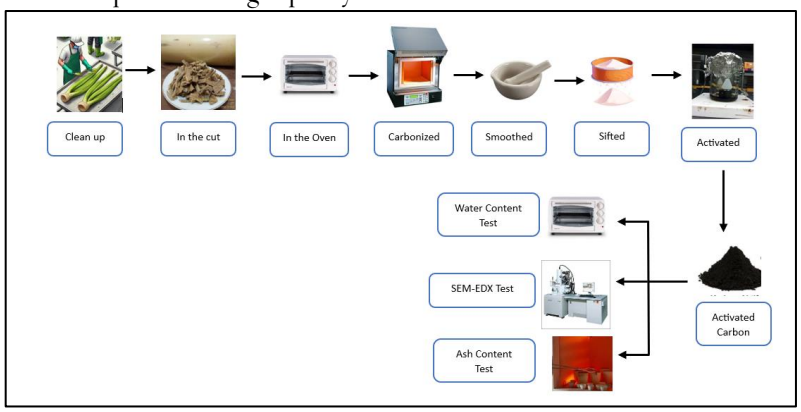

Figure 1. Research Flow Chart

A. Activated Carbon Production Process

The process of making activated carbon in this study began with washing the banana stem until clean, then cutting them into small pieces and drying them in an oven at 105°C (Hatina et al., 2021; Perdani et al., 2021). Next, 80 grams of banana stem were carbonized in an oven at 300°C for 1.5 hours in low-oxygen conditions to produce raw carbon, then sieved using a 100-mesh sieve and weighed (Anggriani et al., 2021; Cintia et al., 2022; Wahyuni et al., 2024). The activation process is carried out by immersing 5 grams of carbonized carbon into 50 ml of NaOH and HCl solutions with varying concentrations of 0.5 M and 1 M (A & Rizki, 2023; Komala et al., 2024). It was then left to stand with activation times varying between 2 and 4 hours. After the activation process, the carbon was drained, filtered, and washed with distilled water until clean, then dried again in an oven at 105°C for 1 hour and weighed (Priambudi & Susanti, 2024; Sa'bandi et al., 2021; Zurairah, 2023). Next, the characteristics of the activated carbon produced were tested through precision testing, which included moisture content, ash content, and morphological and elemental composition analysis using SEM/EDX to determine the quality of banana stem-based activated carbon (Ardi et al., 2021; Ni`maha et al., 2024).

B. Moisture And Ash Content Analysis

1. Moisture Content

Moisture content is the percentage of water that remains bound or absorbed in the pores and on the surface of activated carbon after the drying process, which indicates the moisture level of the material and can affect its adsorption capacity. To calculate the moisture content using equation 1.

$$\text{Moisture content} = \frac{m_1 - m_2}{m_1} \text{ x } 100\% \ldots (1)$$

Where, where m_1 is the mass of the dish and banana stem sample before treatment (g), while m_2 is the mass of the dish and charred banana stem sample after drying in an oven until a constant weight is obtained (g) (Hakiki et al., 2025).

2. Ash Content

Ash content is the percentage of inorganic material remaining after activated carbon is heated at high temperatures, reflecting the mineral content or inorganic impurities in activated carbon, which can affect its quality and adsorption capacity. To calculate the Ash content using equation 2.

$$\text{Ash Content} = \frac{m_3 - m_1}{m_2 - m_1} \text{ x } 100\% \ldots . (2)$$

where m_1 is the mass of the empty dish (in grams), m_2 is the mass of the dish containing the banana stem sample before treatment (in grams), while m_3 is the mass of the dish containing the ash from the combustion of the sample (in grams).(Susanto et al., 2025).

C. Adsorption Test

An adsorption test on activated carbon is a method for determining the ability of activated carbon to adsorb specific substances from a solution by comparing the concentrations before and after the adsorption process.

$$\text{Adsorption (Pb)} = \frac{A_0}{A} \; x \; 100\% \ldots\ldots\ldots (3)$$

Where A_0 is the initial concentration of the solution (ppm), and A is the final concentration of the solution.(Ningsih et al., 2025)

RESULTS AND DISCUSSION

Observe Figure 2, which shows the FT-IR spectrum of banana stem-based activated carbon. The spectrum shows several characteristic absorption bands that indicate the presence of functional groups on the surface of the activated carbon.

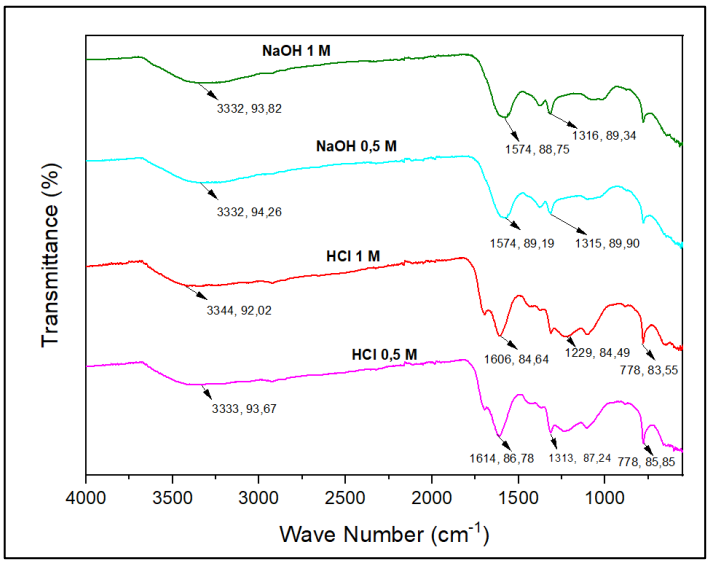

Figure 2. FT-IR results of activated carbon based on banana stem

Based on Figure 2, the FT-IR spectrum of banana stem-based activated carbon treated with NaOH as a basic activator indicates a more intense delignification process and degradation of the lignocellulosic structure, thereby opening more pores and producing a more reactive carbon surface. Consequently, more oxygen groups such as C–O and conjugated C=O are formed and/or exposed, as indicated by the increased intensity of the bands at

around 1574 cm^{-1} and 1315–1316 cm^{-1}. Increasing the NaOH concentration (1 M) further enhances this effect, leading to greater functional group intensity, which in turn increases the polarity and adsorption capacity of the activated carbon. Conversely, the use of HCl as an acid activator tends to play a role in removing minerals (deashing) and hydrolyzing amorphous components without significantly damaging the aromatic carbon structure, making the aromatic structure more dominant and stable, as indicated by the strong band at 1606–1614 cm^{-1} associated with aromatic C=C or C=O. In addition, the appearance of a more pronounced aromatic C–H band at approximately 778 cm^{-1} at a 1 M concentration indicates that HCl activation is able to preserve and even enhance the aromatic character of the carbon, such that an increase in HCl concentration contributes to the dominance of the aromatic structure, which results in increased structural stability and more effective π–π-based adsorption interactions for nonpolar or aromatic compounds.

Refer to Figure 3 and 4, which shows the results of morphological characterization of banana stem-based activated carbon using Scanning Electron Microscopy (SEM). The figure shows the surface structure of activated carbon activated with HCl and NaOH activators at concentrations of 0.5 M and 1 M, respectively, and with activation times of 2 hours and 4 hours.

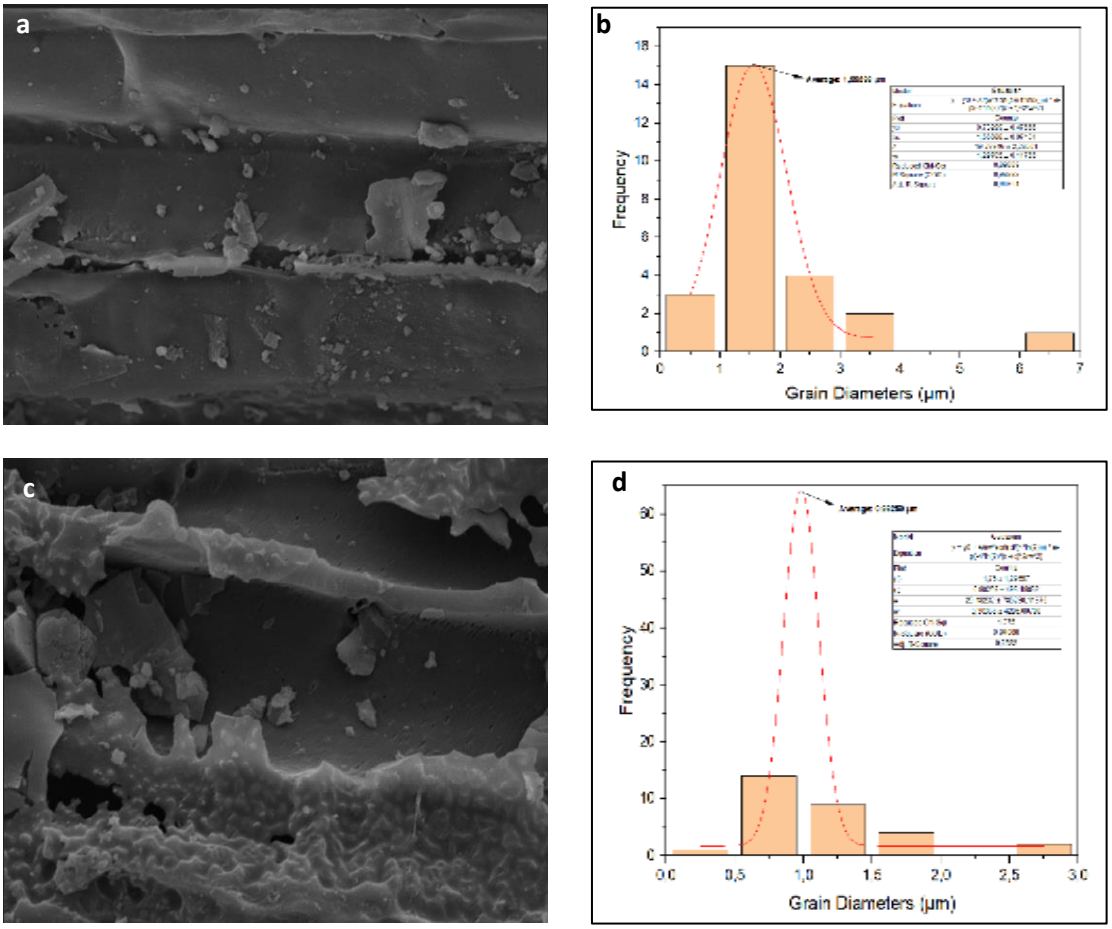

Figure 3. Graphs of banana stem-based activated carbon SEM, (a) Morphology of 0.5 M HCl, (b) Grain Diameters of 0.5 M HCl, (c) Morphology of 1 M HCl, (d) Grain Diameters of 1 M HCl

The SEM-EDX results indicate that increasing the HCl activator concentration from 0.5 M to 1 M has a significant effect on the evolution of the morphology and particle size of activated carbon. Based on Figure 3(a) at a concentration of 0.5 M, the activation process is still limited to the removal of some amorphous and mineral components, so that the carbon surface appears uneven and layered, and the pores formed have not yet developed optimally. Consequently, in Figure 3(b), the structure remains relatively dense with larger particle sizes (average 1.56 µm). Conversely, as shown in Figure 3(c) at a

concentration of 1 M, the increased number of H^+ ions accelerates the hydrolysis and dissolution of non-carbon components (such as hemicellulose, residual lignin, and ash), thereby opening more pores and clarifying the pore network on the carbon surface. This process also causes particle fragmentation into smaller particles with a more homogeneous distribution, as evidenced by the decrease in average size to 0.98 µm, which can be seen in Figure 3(d). Scientifically, this indicates that a higher HCl concentration enhances the effectiveness of activation through deashing and carbon matrix erosion mechanisms, resulting in a more porous structure, greater surface area, and higher adsorption potential.

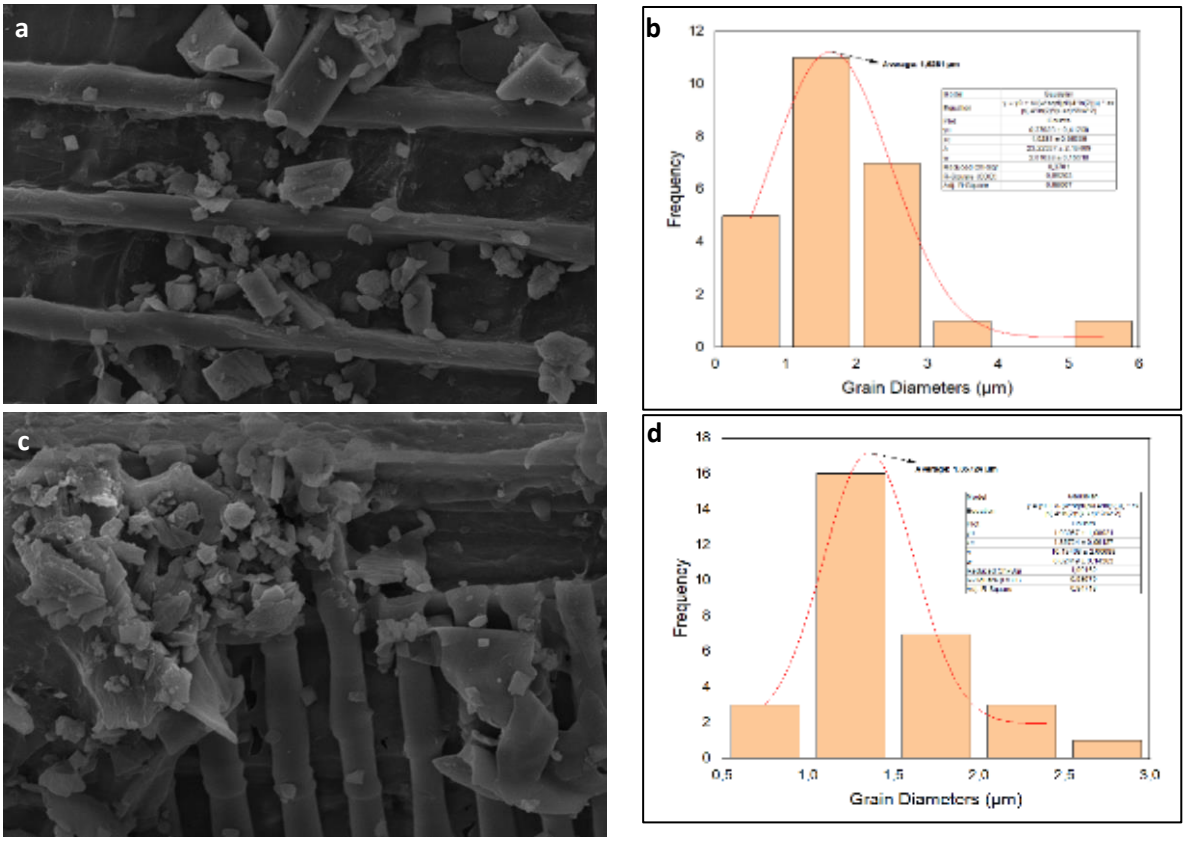

Figure 4. Graphs of banana stem-based activated carbon SEM, (a) Morphology of 0.5 M NaOH, (b) Grain Diameters of 0.5 M NaOH, (c) Morphology of 1 M HCl, (d) Grain Diameters of 1 M NaOH

Based on Figures 4, an increase in the NaOH activator concentration from 0.5 M to 1 M resulted in significant changes in the morphology and particle size of the activated carbon. In Figure 4 (a), activated carbon treated with 0.5 M NaOH exhibits a rough and irregular surface with cracks and pores beginning to form, indicating that the base activation process has occurred but has not yet fully opened the carbon structure. This is supported by Figure 4 (b), which shows relatively larger particle sizes with an average diameter of 1.6 µm. Conversely, in Figure 4(c), the use of 1 M NaOH produces a more open surface with clearer and more developed pores, due to the increased ability of NaOH to dissolve lignocellulosic components and erode the carbon matrix through more intensive chemical reactions. This condition is reinforced by Figure 4(d), which shows a decrease in particle size to an average of 1.35 µm, indicating the fragmentation of particles into smaller sizes and a more homogeneous distribution. Scientifically, this demonstrates that a higher NaOH concentration enhances activation efficiency through delignification and carbon structure degradation mechanisms, resulting in greater porosity, a larger surface area, and higher adsorption potential compared to the 0.5 M concentration.

Based on Figures 3 and 4, activation with NaOH and HCl reveals differences in the mechanisms and morphological outcomes of activated carbon. NaOH (base) acts more aggressively in degrading the lignocellulosic structure, resulting in more developed pores and a more open surface, with particle size decreasing from 1.6 µm to 1.35 µm. Meanwhile, HCl (acid) plays a greater role in the deashing and hydrolysis of amorphous components,

resulting in a more homogeneous structure with a smaller particle size, from 1.56 µm to 0.98 µm. Thus, NaOH is more effective at increasing porosity and surface area, while HCl is more effective at refining particle size and improving the structural homogeneity of activated carbon.

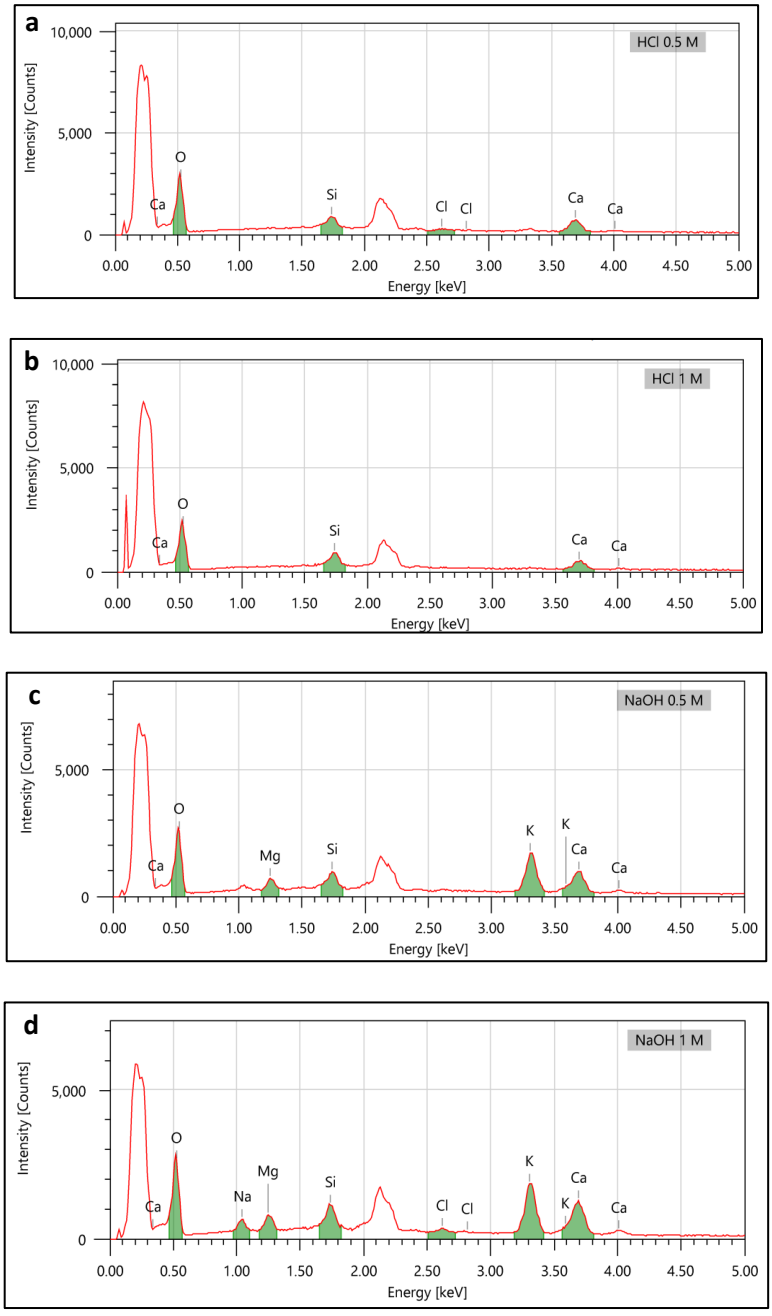

Figure 5. EDX Spectrum of Activated Carbon based on Banana Stem

Based on Figure 5, a comparison of the EDX results shows that activation using HCl and NaOH yields different levels of carbon purity due to the chemical mechanisms involved. HCl (acid) activation is more effective in the deashing process—that is, dissolving inorganic minerals such as Ca and Si—resulting in a spectrum dominated by C and O with very low impurity content. Conversely, NaOH (base) activation tends not to completely remove minerals; it may even leave behind residues of elements such as Na, K, and Mg, particularly at a 1 M concentration, due to the interaction of the base with inorganic components and the potential formation of residual compounds. This indicates that

HCl is superior in enhancing the purity of activated carbon, whereas NaOH plays a greater role in structural modification but has the potential to leave inorganic residues.

Refer to Table 1, which presents the results of EDX analysis on banana stem-based activated carbon, where the data shows the composition of the constituent elements of the material after the activation process, particularly the carbon and oxygen content.

Table 1. EDX Results of Activated Carbon based on Banana Stem

No	Activator (M)	Element	Massa (%)	Atom (%)
1	HCl 0,5	C	42,64±0,51	49,76 ± 0,59
		O	57,36±1,27	50,24 ± 1,11
2	HCl 1	C	45,56 ± 0,55	52,71 ± 0,63
		O	54,44±1,34	47,29 ± 1,17
3	NaOH 0,5	C	40,72 ± 0,54	47,78 ± 0,64
		O	59,28±1,37	52,22 ± 1,20
4	NaOH 1	C	37,23 ± 0,55	44,14 ± 0,66
		O	62,77 ± 1,42	55,86 ± 1,27

Based on Table 1, activation using HCl and NaOH shows clear differences in the carbon (C) and oxygen (O) content of the activated carbon. In HCl activation, there was an increase in carbon content from 42.64% (0.5 M) to 45.56% (1 M), accompanied by a decrease in oxygen content, indicating that the acid activation process is increasingly effective in removing inorganic impurities and non-carbon groups (deashing), thereby producing activated carbon with higher carbon purity. Conversely, in NaOH activation, the carbon content actually decreased from 40.72% (0.5 M) to 37.23% (1 M), while the oxygen content increased, indicating that base activation tends to introduce or retain more oxygen functional groups on the surface, as well as the possible presence of inorganic residues from the activator. This suggests that HCl is more effective in improving the purity of activated carbon, whereas NaOH plays a greater role in enriching surface oxygen groups, which can enhance polar properties and reactivity, albeit at the cost of lower carbon purity.

Refer to Table 2. This table presents the results of data analysis of moisture content and ash content of activated carbon based on banana stem activated using HCl and NaOH activators with varying concentrations and activation times. The data in Table 2 show differences in moisture content, ash content, and average particle size (morphology) produced by each activator, reflecting the effect of activator type and activation conditions on activated carbon quality.

Table 2. Data on Moisture Content, Ash Content, and Average Morphology Test Results

Moisture Content		Ash Content		average morphology	
NaOH (%)	HCl (%)	NaOH (%)	HCl (%)	NaOH (μm)	HCl (μm)
1,68	1,84	20	10	1,63	1,55
1,96	3,13	20	10	1,36	0,98

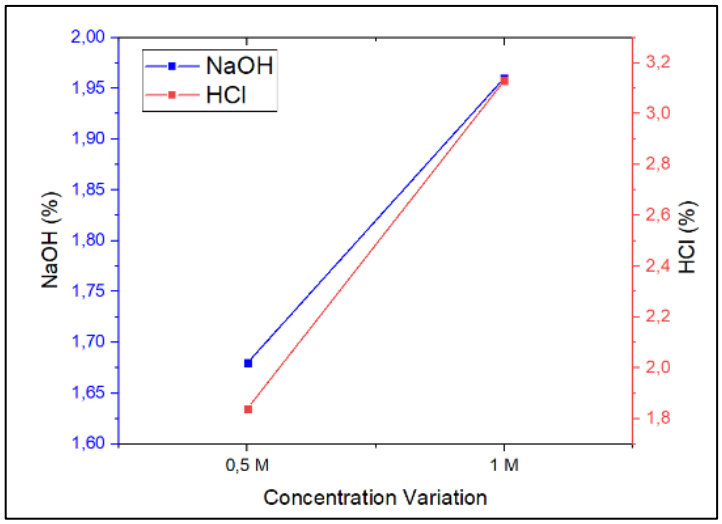

Figure 6. Moisture Content Test Results Data

As shown in Figure 6, an increase in the concentration of NaOH as a basic activator causes the degradation of lignocellulose and the formation of hydrophilic functional groups such as –OH to proceed more intensively, making the carbon surface more prone to binding water. Consequently, the moisture content of activated carbon increased from approximately 1.68% at a concentration of 0.5 M to 1.96% at 1 M. Meanwhile, in HCl activation, an increase in concentration accelerates the deashing process and pore opening, thereby enhancing the material's ability to absorb water, although not as strongly as the effect of hydrophilic group formation in the base. Consequently, the moisture content increased from approximately 1.63% at 0.5 M to 1.96% at 1 M. A lower moisture content is preferable as it indicates drier and more stable activated carbon. When compared to SNI Standard No. 06-3730-1995, which requires a maximum moisture content of 15%, all samples—whether activated using NaOH or HCl—met this standard. However, at low HCl concentrations, the quality was slightly better than that achieved with NaOH, whereas at high concentrations, both methods yielded relatively similar quality.

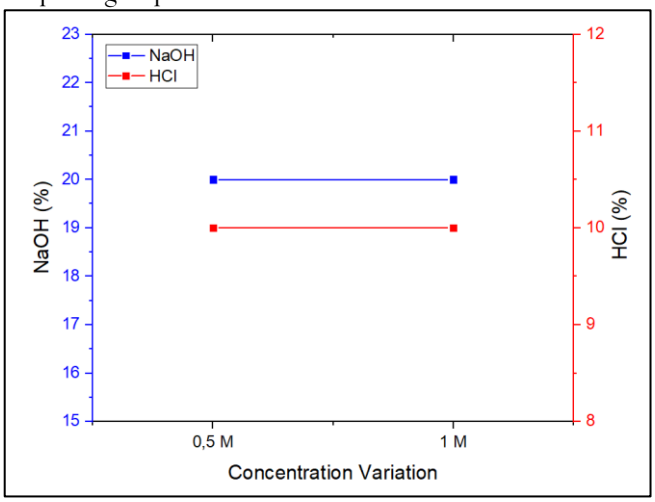

Figure 7. Ash Content Test Results Data

Based on Figure 7, the difference in ash content between NaOH and HCl activation is due to the different chemical mechanisms of the two agents on the inorganic components in the material. NaOH (base) activation tends to be less effective in dissolving inorganic minerals; it can even lead to the formation of residues such as sodium compounds left behind on the carbon structure, resulting in a relatively high ash content that does not undergo significant change—approximately 20% at both 0.5 M and 1 M concentrations. Conversely, HCl (acid) activation is more effective in the deashing process

because it can dissolve minerals such as Ca and Mg, resulting in a lower and more stable ash content, namely around 10% at both concentrations. When compared to the activated carbon quality standard based on SNI No. 06-3730-1995, which requires a maximum ash content of 10%, the activated carbon produced by HCl activation meets this standard, whereas NaOH activation does not because its ash content remains too high. Thus, HCl activation is superior as it produces activated carbon with higher purity.

Refer to Table 3, which summarizes previous studies discussing the characteristics of activated carbon.

Table 3. Previous studies discussing activated carbon

No	Material	Solvent	Moisture Content (%)	Ash Content (%)	References
1	Coffee Grounds	HNO_3	4,5	7,7	(‘Aisy et al., 2025)
	Durian Skin	HNO_3	3,9	6,8	
2	Water Hyacinth Stem	NaOH	4,39	8,1	(Azis et al., 2025)
3	Oil Palm Trunk	NaOH 5%	3,39	10,7	(Amna & Lestari, 2025)
		NaOH 10%	1,19	10,5	
		NaOH 15%	1,38	8,4	
4	Coffee Bean Husk	NaOH 2M	5,8	7,03	(Dwi et al., 2025)
		NaOH 3 M	3,8	6,01	
		NaOH 4 M	2,5	5,5	
5	Durian Skin	KOH 25%	22,7	36,7	(Rahmawati et al., 2025)

Based on Table 3, previous studies have shown that the quality of activated carbon is influenced by raw materials and the type and concentration of activators. Activation using HNO_3 and NaOH with controlled concentrations generally produces relatively low moisture and ash content. Conversely, the use of KOH with high concentrations produces very high moisture and ash content, indicating suboptimal activation.

An analysis of the adsorption capacity of banana stem-based activated carbon for lead (Pb) was conducted using the Atomic Absorption Spectrophotometry (AAS) method. This method was used to determine the concentration of lead remaining in the solution after the adsorption process. To obtain this concentration value, the absorbance of the adsorbed solution was first measured, and then the obtained absorbance data was plotted on a calibration curve prepared using standard Pb solutions. Using this calibration curve, the absorbance values could be converted into the final concentration of Pb in the solution. Furthermore, based on a comparison between the initial and final concentrations, the adsorption efficiency of the activated carbon can be determined. The results of the adsorption test of the standard Pb metal solution for each treatment are presented in Table 4.

Table 4. Adsorption of Lead (Pb) Standard Solutions

No	Adsorption	Concentration (ppm)
1	0,000	0,000
2	0,085	0,100
3	0,198	0,300
4	0,315	0,500
5	0,420	0,700
6	0,580	0,900

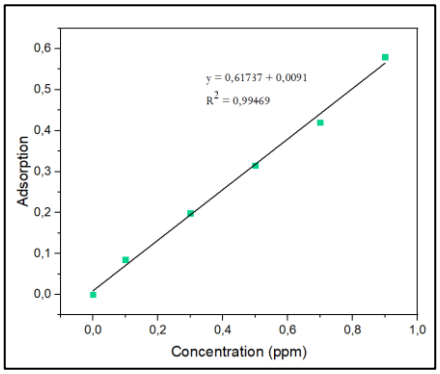

Figure 8. Calibration Curve for Pb Solution

Based on Figure 8, the calibration curve for the Pb solution shows a positive linear relationship

between concentration and absorbance, such that as the Pb concentration increases, the absorbance value also increases. The regression equation obtained is y = 0.61737x + 0.0091 with a coefficient of determination R^2 = 0.99469, indicating an excellent level of linearity and accuracy. An R^2 value close to 1 indicates that this curve is suitable for use as a reference in determining Pb concentration.

Table 5. Adsorption Test of Activated Carbon from Banana Stems

No	Activator (M)	Adsorption (%)
1	HCl 0,5	61,50
2	HCl 1	72,50
3	NaOH 0,5	56,00
4	NaOH 1	49,00

Based on Table 5, activated carbon activated using HCl exhibited higher adsorption capacity compared to NaOH. With the HCl activator, adsorption efficiency increased from 61.50% (0.5 M) to 72.50% (1 M), indicating that an increase in acid concentration enlarges and cleans the carbon pores, thereby increasing the effective surface area for Pb ion adsorption. Conversely, with the NaOH activator, adsorption efficiency decreased from 56.00% (0.5 M) to 49.00% (1 M). This indicates that base activation at high concentrations tends to produce a more hydrophilic surface with a high content of hydroxyl groups (–OH), causing the pores to be more easily filled by water molecules and inhibiting the diffusion of Pb ions into the pores.

This difference indicates that acid activation (HCl) is more effective in improving the pore structure and surface purity of activated carbon, whereas base activation (NaOH) at high concentrations can actually reduce adsorption performance due to increased water content, ash, and hydrophilic properties. Thus, HCl, particularly at a concentration of 1 M, is the most optimal activator for enhancing the adsorption capacity of banana stem-based activated carbon toward Pb.

CONCLUSION AND SUGGESTIONS

Based on the results of the study, it can be concluded that banana stem-based activated carbon was successfully synthesized through a chemical activation process using HCl and NaOH with varying concentrations and activation times, and exhibited different physical and chemical characteristics. FT-IR results identified the presence of main functional groups such as –OH, C=O, aromatic C=C, and C–O in all samples, which supports the potential of activated carbon as an adsorbent. Overall, activation using HCl, particularly at a concentration of 1 M with an activation time of 4 hours, produced banana stem activated carbon with the most optimal quality and high potential for adsorption applications in the environmental and materials fields. SEM characterization showed that increasing the concentration and activation time affected pore formation and surface morphology refinement, with 1 M HCl activated carbon producing the smallest particle size and more uniform pore structure. EDX analysis confirmed that the material was dominated by carbon and oxygen elements, with oxygen-containing groups acting as active adsorption sites. Meanwhile, all samples met the moisture content requirements according to SNI No. 06-3730-1995, but only activated carbon using HCl met the ash content standard, indicating better quality compared to NaOH activation. In addition, the results of the adsorption tests for lead (Pb) showed that activated carbon treated with HCl performed better than that treated with NaOH; specifically, the adsorption efficiency increased from 61.50% to 72.50% with HCl, whereas it decreased from 56.00% to 49.00% with NaOH, making 1 M HCl the most optimal condition.

WORDS OF THANKS

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