

## High surface area bamboo biochar production using a stainless-steel reactor enclosed with clay bricks

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### ✉ \* CORRESPONDING

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### ABSTRACT

Bamboo is a renewable and abundant agricultural resource with strong potential for producing high-value materials such as biochar. However, high volatile matter content and low BET surface area limit the biochar's effectiveness in environmental applications. This study aims to enhance the properties of bamboo biochar using a stainless-steel reactor enclosed with clay brick, followed by methanol modification. Bamboo feedstock was cut, sun-dried, and carbonized at 900 °C for 5 hours to produce biochar, which was then treated with methanol to improve surface characteristics. Proximate analysis showed an increase in fixed carbon from raw bamboo to bamboo biochar and methanol-modified bamboo biochar from 12.65±0.69 to 57.13±0.78 and 58.88±0.43 wt.% respectively, and a decrease in volatile matter from 77.03±0.60 to 33.97±0.80 and 32.40±0.45 wt.% respectively. Ultimate analysis revealed an increase in carbon content from raw bamboo to bamboo biochar and methanol-modified bamboo biochar from 45.18±2.75 to 71.46±3.89 and 73.68±2.99 wt.% respectively and decreases in oxygen content after carbonization and methanol treatment. The BET surface area was observed with a significantly increase from 3.88±0.45 m<sup>2</sup>/g of raw bamboo to 256.75±39.80 m<sup>2</sup>/g of bamboo biochar and further increased to 343.84±2.14 m<sup>2</sup>/g in methanol bamboo biochar. Correspondingly, the pore volume of raw bamboo to methanol-modified bamboo biochar increases from 0.001±0.001 to 0.17±0.02 cm<sup>3</sup>/g and pore diameter decreases from 2.07±1.88 to 1.86±0.06 nm respectively. SEM images illustrated the development of relatively smooth surface and well-developed porous structure compared to raw bamboo surface. FTIR analysis indicates that the presence of functional groups (C–O, O–H, C–C) which confirms that changes in chemical and structural modification after carbonization and methanol modification. These results indicate that slow carbonization process with methanol modification significantly enhances the physiochemical characteristics of bamboo biochar and makes it a strong potential adsorbent for environmental pollutant removal.

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## 1. INTRODUCTION

Bamboo (*Dendrocalumus asper*) is a rapidly growing woody grass from the Poaceae family, widely utilized for its diverse applications in construction, furniture, and environmental remediation. The high adaptability of bamboo makes it widely cultivated across Asia (Ku Aizuddin et al., 2023). In Malaysia, bamboo resources occupy approximately 229,123 hectares in Peninsular Malaysia (31%), 177,385 hectares in Sabah (24%), and 332,597 hectares in Sarawak (45%) (Bernama, 2021). This regional distribution highlights its potential as a sustainable biomass source for production of biochar. The presence of high cellulose, hemicellulose and

lignin content makes it suitable feedstock for biochar production through gasification and pyrolysis (Kakati et al., 2022). These thermochemical processes usually operate at high temperature ranging from 800 to 1200°C enabling bamboo to serve as viable alternative for wood in charcoal production (Hernandez-Mena et al., 2014; Jalil et al., 2022). However, conventional pyrolysis requires higher energy input to maintain high carbonization temperature in a oxygen-limited environment (Aijen et al., 2023). Therefore, this highlights the requirement of low-energy biochar production approaches. Self-sustained carbonization represents one approaches where biomass is heated under limited oxygen conditions to

sustain the process without relying with external electrical input, enabling biochar production with lower energy input (Samsudin et al., 2019). Nevertheless, fluctuations in carbonization temperature may affect the development of desirable optimal surface characteristics which is necessary for modification process that allows the improvement of biochar physiochemical properties for environmental applications.

The production of bamboo biochar using a stainless-steel reactor enclosed with clay bricks presents a novel, efficient, and sustainable method for biomass conversion. This hybrid design synergizes the strengths of both materials, the durability and thermal conductivity of stainless steel with the insulation and affordability of clay bricks. The system is particularly suited for community-scale or semi-industrial applications and offers several advantages, especially in enhancing biochar quality, energy efficiency, and environmental impact. The stainless-steel enclosure from the reactor offers several advantages compared to other conventional reactors systems. Stainless steel is commonly used material in chemical and environmental equipment because of its good resistance of corrosion, mechanical strength and capability to tolerate high temperatures, maintaining long term durability and operational reliability in chemical environments (Outokumpu Oyj, 2013). Stainless steel contains chromium which creates a corrosion-protective layer on its surface that enhances the material durability (Ren et al., 2023). Furthermore, stainless steel reactor possess excellent thermal stability and efficient heat transfer capability which enable consistent temperature distribution and enhancing energy efficiency during operation (Towler & Sinnott, 2013).

The property of biochar produced from this carbonization process can also be enhanced through various modification techniques, including chemical, magnetic, physical, and metal oxide impregnation methods (Godwin et al., 2019). Among these, chemical modification is commonly used and involves agents such as phosphoric acid ( $H_3PO_4$ ), potassium hydroxide (KOH), sodium hydroxide (NaOH), and zinc chloride ( $ZnCl_2$ ). Recent studies have also explored the use of methanol and ethanol as alternative modifying agents, with methanol identified as a cost-effective option for improving surface functional groups and enhancing adsorption efficiency (Godwin et al., 2019; Hasana et al., 2021).

To evaluate the bamboo biochar and modified bamboo biochar produced, physicochemical characterization is required. The physicochemical characterization includes proximate analysis (moisture, volatile matter, ash and fixed carbon), ultimate analysis (carbon, hydrogen, nitrogen, and oxygen), surface area analysis (BET surface area, pore

volume and pore size), functional group analysis and FESEM (Field Emission Scanning Electron Microscope) morphological analysis. For proximate analysis, moisture content is the amount of water content inside the biochar which could affect the heating value, and adsorption efficiency. Higher value of moisture content is not desirable due to more energy is required for water removal that will decrease the overall efficiency of the raw material (Mierzwa-Hersztek et al., 2019; Tomczyk et al., 2020). As for volatile matter, it refers to organic compounds that are released in gaseous form when biochar is heated with limited oxygen conditions. Higher volatile matter proves an incomplete carbonization of the biochar while low volatile matter shows a better thermal decomposition and enhanced structural stability of the biochar. For example, volatile matter of the bamboo biochar sample decreases as the carbonization temperature increases (Sahoo et al., 2021; Wang et al., 2018). For fixed carbon, it is the remaining of solid carbonaceous residue after moisture and volatile matter removal which shows the biochar stable carbon structure (Fawzy et al., 2021). Increase in fixed carbon shows better thermal stability, high heating value and will beneficially improves the adsorption performance due to condensed aromatic carbon structure that are presence within the biochar (Xiao et al., 2016). Ash content represents the inorganic mineral residue remaining after a complete combustion. The heating value and BET surface area of biochar may be reduced due to higher ash content even though some mineral components can promote to adsorption performance with ion exchange mechanism or chemical interactions (Tomczyk et al., 2020).

For ultimate analysis, carbon content is the organic material of the primary components which determines the structural framework and content of energy of the biochar or biomass. High content of carbon linked to aromatic structures which influences the adsorption capacity as carbon-rich surfaces that gives sites of  $\pi$ - $\pi$  interactions with organic pollutant presence in the wastewater (Lehmann & Joseph, 2015). Hydrogen content is the saturation of hydrocarbons and implies the aliphatic structures of the sample. Hydrogen promotes to the surface polarity and reactivity, affecting the interactions with water-soluble pollutants. High hydrogen content shows a less thermally stable biochar which will affect the adsorption performance (Mohan et al., 2017). Nitrogen content is the protein or amino components of the materials. Nitrogen-containing groups can produce a basic sites on the surface of biochar, which will enhance the adsorption of acidic type contaminants such as dye and heavy metals (Ahmad et al., 2012). Nitrogen presence also contributes to cation exchange capacity (CEC), a significant factor in water treatment systems. As for oxygen content, it is percentage of oxygen in the sample and present as functional groups ( $-OH$ ,

–COOH, –C=O) which strongly influences the hydrophilicity, acidity and adsorption behavior. Oxygen-containing functional groups are essential in hydrogen bonding, complexation and electrostatic interactions in aqueous solution (Wang et al., 2022). Low oxygen content in biochar has less active sites and low adsorption capacity while high oxygen content will easily bind the pollutants from the water due to hydrogen bonding and electrostatic attraction (Dai et al., 2021).

Surface area and porosity analysis are key physical characteristics of biochar that contribute to adsorption performance. High BET surface area and well-developed porosity will produce more active sites and improve the mass transfer pathways for binding of pollutants, and will increase the adsorption efficiency (Irewale et al., 2025). Pyrolysis causes the breakdown of biomass which releases volatile organic matter and forms pores, which increase the surface area and pore volume (micropores and mesopores). Different pyrolysis conditions such as residence time, temperature and type of raw materials, strongly influence the characteristics of biochar. For example, optimal conditions will produce a combination of mesopores and micropores for improving the materials adsorption of small and large molecules (Irewale et al., 2025).

Functional group analysis is to determine the presence of surface oxygen-containing functional groups such as carboxyl (–COOH), hydroxyl (–OH), ether (C–O–C), aromatic (C=C) and ether (C–O–C). This type of functional group is essentially important for adsorption mechanisms which are complexation, electrostatic attraction, ion exchange and hydrogen bonding with target pollutant in aqueous solution (Yaashikaa et al., 2020). For example, oxygen-containing functional groups can contribute to removal of dissolved metal ions via complexation and electrostatic interactions which lead to higher adsorption of heavy metals. Hydroxyl groups serve to enhance hydrophilicity and promote the interactions of polar molecules and ions while carboxyl and phenol groups serve as coordination sites for heavy metals. The presence and amount of the functional groups strongly influence the pyrolysis conditions and type of feedstocks, with increase in temperature will improve the aromatic structures and could reduce the reactive surface functionalities, thus affecting the adsorption behaviour (Chakma et al., 2025).

The morphological analysis is to visualize the surface texture and structural features of the biochar at various high magnification. SEM images provide the pore formation, roughness of the surface, particle shape and microstructural heterogeneity that will influence the adsorption performance.

A porous structure provides a higher accessible surface area, which provides more adsorption sites (Osman et al., 2022; Ndoun et al., 2021). Besides, the pores network enables adsorbates to diffuse into internal pores which then

improves the interaction between the adsorbate and adsorbent. This effective diffusion is essential for efficient mass transfer and favorable adsorption kinetics in aqueous solutions (Shi et al., 2023).

Literature reviews indicate that few studies have investigated the production of bamboo biochar using a stainless-steel brick reactor or its subsequent modification with methanol (Hasana et al., 2021). Nonetheless, pilot-scale carbonization stainless-steel reactor enclosed with clay brick to reduce heat loss is still limited. Therefore, this study aims to produce bamboo biochar using a stainless-steel brick reactor enclosed with clay bricks, followed by methanol modification. The physicochemical properties of raw bamboo, bamboo biochar and methanol-modified bamboo biochar will be analyzed and characterized to determine their effectiveness for various biochar applications.

## 2. MATERIALS AND METHODS

### 2.1 Sample Preparation

Raw bamboo (*Dendrocalamus asper*) was collected from a small plantation in Kampung Quap (10th Mile), Kota Samarahan, Sarawak (1°25'08.7"N 110°20'41.3"E). The collected bamboo was cut into small pieces ranging from 10 to 20 mm and sun-dried until the moisture content was below 5% (w/w) prior to carbonization.

### 2.2 Experimental Setup

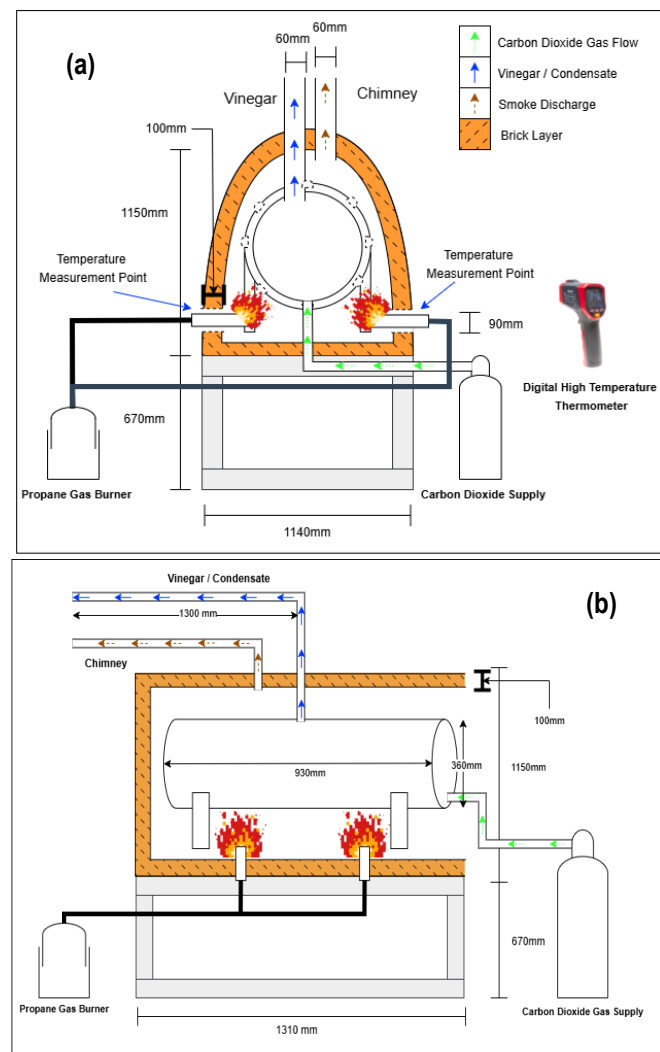
#### 2.2.1 Stainless-steel reactor enclosed with clay brick

Slow carbonization was performed using a pilot-scale stainless-steel reactor (930 mm length × 360 mm width) enclosed within clay brick walls (1140 mm length × 1310 mm width × 1150 mm height; 100 mm thick) as shown in Figure 1. The reactor was sealed with stainless steel to minimize oxygen pressure and insulated with clay brick to reduce heat loss. The temperature measurement was taken at the temperature measurement point with digital high temperature thermometer. Carbonization was conducted at a constant temperature of 900 °C for 5 hours using a gas burner. A stainless-steel chimney pipe (60 mm diameter) connected to the stainless-steel reactor was used to condensate the vinegar, meanwhile another chimney pipe (60 mm diameter) was connected to the clay brick walls to release gaseous emissions.

To ensure an efficient carbonization process, nitrogen gas was purged into the stainless-steel reactor to reduce oxygen concentration within the chamber. Approximately three-quarters of the pilot-scale stainless-steel reactor chamber was filled with dried bamboo pieces ranging from 10 to 20 mm. After carbonization, the bamboo biochar was allowed to cool down for 24 hours before further analysis.

## 2.3 Methanol Modification

The methanol modification procedure was conducted according to Hasana et al. (2021) and Oh et al. (2004). Methanol was used to improve the physiochemical characteristics of biochar produced from stainless-steel brick reactor.



**Figure 1:** Stainless-steel reactor enclosed with brick layer: (a) front view; and (b) side view

Methanol modification can increase the surface characteristics of biochar by eliminating the residual impurities and enhancing the formation of pores on the biochar surface. This process can enhance the specific surface area and improve the accessibility of adsorption sites, which play an important role in pollutant removal in wastewater treatment applications. Furthermore, methanol treatment may introduce functional groups of the biochar surface, which can improve its interaction with organic and inorganic pollutants. Methanol was considered an efficient solvent for surface modification because of its low cost, high volatility and effective porous structures (Ahmad et al., 2014; Tan et al., 2015). Thus, this study applied methanol modification to improve the surface properties and adsorption performance of bamboo-derived biochar.

## 2.4 Characterization

The proximate analysis was conducted as per ASTM Methods to determine the moisture content, volatile matter ash content and fixed carbon for biomass and biochar samples. The raw bamboo was determined based on ASTM standards: ASTM E871, ASTM E872 and ASTM D1102. As for biochar samples, it was determined based on ASTM standards: ASTM D5142. The ultimate analysis which contains carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O) was determined by using CHNS/O Organic Elemental Analyzer (Flash 2000, ThermoFisher CHONS) with approximately 2 g of each sample sealed in aluminum capsules and analyzed at 1000 °C.

The BET surface area, pore size and pore volume was determined using Brunauer-Emmett-Teller (BET) gas adsorption analyzer (Micromeritics 3Flex) with nitrogen adsorption. The functional groups of biomass and biochar samples were analysed with Fourier Transform Infrared Spectroscopy (FTIR) (Perkin Elmer Frontier). The surface morphology of all the samples was determined using Extreme High-Resolution Field Emission Scanning Electron Microscope (XHR-FESEM) (Model FEI Verios 460L) at 2500× magnification.

## 3. RESULT AND DISCUSSION

### 3.1 Proximate analysis

Table 1 shows that raw bamboo, bamboo biochar under slow carbonization, and methanol-modified bamboo biochar result in a notable reduction in moisture and volatile matter contents, alongside an increase in ash and fixed carbon contents. The moisture content decreased from  $9.48 \pm 0.07$  wt% in raw bamboo to  $2.29 \pm 0.19$  wt% in bamboo biochar, indicating effective drying during the carbonization process. Following the slow carbonization and methanol modification, the volatile matter content decreased significantly from  $77.03 \pm 0.60$  wt% of raw bamboo to  $32.40 \pm 0.45$  wt% of methanol-modified bamboo biochar due to thermal decomposition of volatile organic compound during carbonization process.

Meanwhile, the ash content of  $1.24 \pm 0.08$  wt% for raw bamboo increases to  $6.54 \pm 0.17$  wt% of bamboo biochar after carbonization, indicating the concentration of inorganic mineral residue. Fixed carbon content showed a significant rise from  $12.25 \pm 0.69$  wt% to  $57.13 \pm 0.78$  wt%, indicating improvement in thermal stability and greater energy retention. These observations are consistent with previous studies and demonstrate the use of slow carbonization followed by methanol modification can effectively generate a carbon-rich and stable bamboo biochar. The decrease in moisture and volatile matter, along with rise in ash content and fixed carbon

content indicates that the success of thermal conversion from raw bamboo to bamboo biochar.

Nevertheless, the fixed carbon content in this research ( $57.13 \pm 0.78$  –  $58.80 \pm 0.43$  wt%) is lower than reported by Sahoo et al. (2021), who recorded 81.85–83.70 wt.%, and by Hernandez-Mena et al. (2014), who observed 81.50 wt.%. The differences may result from variations in reactor design, contact time and heating rate which can affect the degree of carbonization. For instance, Sahoo et al (2021) uses fixed-bed reactor for thermal conversion. Furthermore, the ash content in this present study ( $6.44 \pm 0.08$  –  $6.54 \pm 0.17$  wt%) is higher than those reported by Sahoo et al. (2.98 – 4.65 wt.%) and Hernandez-Mena et al. (2014) (3.90 wt.%), which could be attributed with differences in feedstock composition or inorganic content of *Bambusa* species. The moisture content of biochar samples in this study ( $2.10 \pm 0.02$  –  $2.29 \pm 0.19$  wt.%) is within the range values (1.28 – 4.17 wt.%) reported by Sahoo et al. (2021), indicating that the production of biochar in this study was effectively decreasing the moisture content and produce a relatively dry and stable carbon adsorbent for adsorption treatment.

### 3.2 Ultimate analysis

Table 2 shows that slow carbonization and methanol modification significantly altered the bamboo elemental properties. Carbon content increased from  $45.18 \pm 2.75$  wt.% in raw bamboo to  $71.46 \pm 3.89$  wt.% in bamboo biochar, with a slight increase to  $73.68 \pm 2.99$  wt.% in methanol-modified bamboo biochar, indicating an overall carbon enrichment. Meanwhile, hydrogen content decreased sharply from  $6.99 \pm 1.78$  wt.% in raw bamboo to  $0.98 \pm 0.11$  wt.% in bamboo biochar, with a further decline to  $0.84 \pm 0.08$  wt.% in methanol-modified bamboo biochar. Oxygen content decreased from  $47.21 \pm 1.22$  wt.% in raw bamboo to  $27.57 \pm 3.85$  wt.% in bamboo biochar, followed by a slight decrease to  $25.86 \pm 2.71$  wt.% in methanol-modified bamboo biochar. The increase in carbon content and corresponding reduction in hydrogen and oxygen in the biochar samples confirms successful aromatization and carbon concentration during carbonization. The carbon content in the present study ( $71.46 \pm 3.89$  –  $73.68 \pm 2.99$  wt.%) is appreciably higher than the raw bamboo ( $45.18 \pm 2.75$  wt.%) but still lower than those reported by Sahoo et al. (2021) (81.85–85.16 wt.%) and Hernandez-Mena et al. (2014) (81.50 wt.%). This discrepancy may be due to differences in bamboo species, heating rates, and pyrolysis methods, such as the use of fixed-bed or muffle furnace reactors in other studies (Sahoo et al., 2021; Hernandez-Mena et al., 2014). Furthermore, the significant drop in hydrogen and oxygen reflect enhanced thermal stability and a higher degree of carbonization. A similar trend was reported by Wang et al. (2018), which is a reduction in

hydrogen and oxygen content due to increase in pyrolysis condition. Furthermore, the nitrogen content had remained relatively low for all sample which is consistent with other studies and suggesting the limited in nitrogen during pyrolysis process of lignocellulosic feedstock (Wang et al., 2018).

### 3.3 Surface area analysis

Table 3 presents a substantial enhancement in the surface properties of bamboo biochar following slow carbonization and subsequent methanol modification. Brunauer–Emmett–Teller (BET) surface area increased markedly from  $3.88 \pm 0.45$  m<sup>2</sup>/g in raw bamboo to  $256.75 \pm 39.80$  m<sup>2</sup>/g after slow carbonization and further increased to  $343.84 \pm 2.14$  m<sup>2</sup>/g following methanol treatment. Total pore volume exhibited a similar trend, rising from  $0.001 \pm 0.001$  cm<sup>3</sup>/g in raw bamboo to  $0.09 \pm 0.05$  cm<sup>3</sup>/g in bamboo biochar and then to  $0.17 \pm 0.02$  cm<sup>3</sup>/g after methanol treatment. The average pore diameter slightly decreased from  $2.07 \pm 1.88$  nm in raw bamboo to  $1.16 \pm 0.47$  nm after carbonization, then increased to  $1.86 \pm 0.06$  nm after methanol treatment.

These results indicate that the carbonization process enhanced the thermal decomposition of hemicellulose and cellulose present in the bamboo structure. The process led to release of volatile compounds and formation of an initial porous carbon matrix. The decrease in pore diameter after carbonization indicates that developments of mainly microporous structures, which are typically formed during pyrolytic conversion of lignocellulosic biomass. After carbonization stage, methanol modification further improved the textural characteristics of biochar, as indicated by the increase BET surface area and total pore volume.

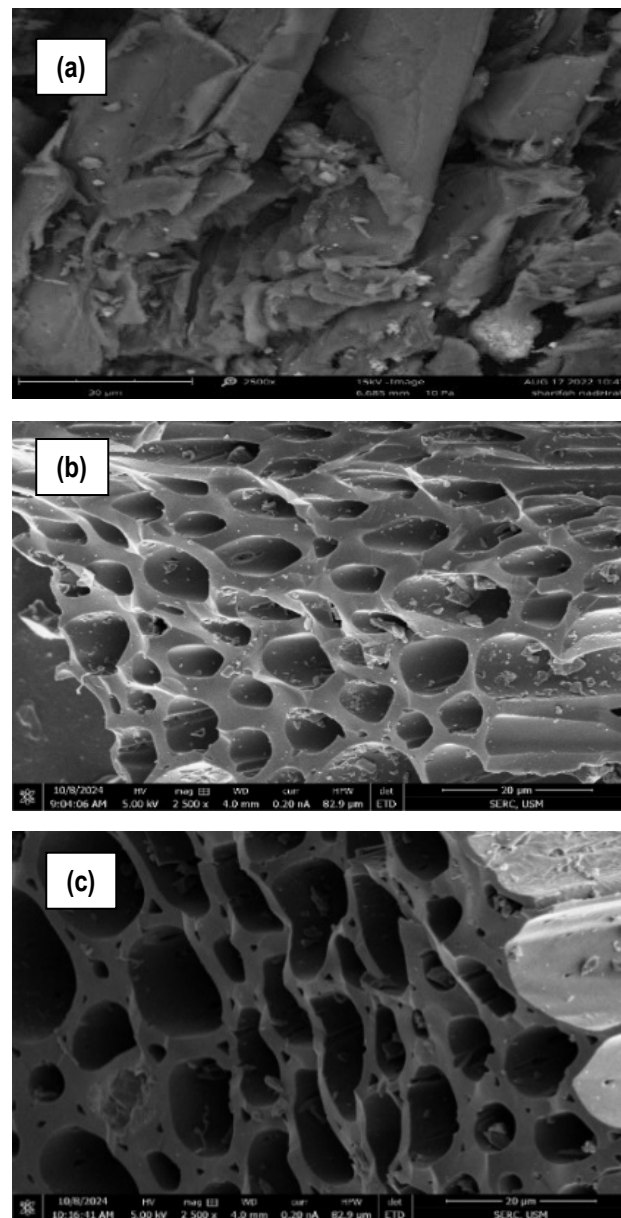
Methanol treatment likely penetrated the carbon matrix and removed remaining tar residues, ash and volatile compounds that may block the pores created during carbonization. Consequently, previous blocked pores became accessible, which improves pore accessibility and promotes more interconnected porous structures. Furthermore, the slight increase in average pore diameter following methanol treatment may indicate partial pore widening, which enhances the diffusion of adsorbate molecules into the internal pore structure. These structural improvements are advantageous for adsorption processes because well-developed pore structure provides more active adsorption sites (Ahmad et al., 2014; Tan et al., 2015). These enhancements in terms of surface area suggest that the combined process of slow carbonization and methanol modification can significantly improve the porosity and surface characteristics of bamboo biochar, thus improving its potential for application such as adsorption and environmental applications treatment.

In comparison with previous studies, this present

study shows a significant improvement in surface area, especially for bamboo biochar produced by slow carbonization and methanol modification. The BET surface area of bamboo biochar ( $256.75 \pm 39.90 \text{ m}^2/\text{g}$ ) for this study within the higher range reported by Sahoo et al. (2021) and significantly higher than Wang et al. (2018) and Hernandez-Mena et al. (2014), highlighting the effectiveness of controlled thermal processing in promoting pore development. Previous studies have reported that surface area of bamboo biochar is highly influenced on the pyrolysis temperature and heating rate, as this parameter controls the decomposition of lignocellulosic components and the release of volatile compounds during carbonization process (Wang et al., 2018). During the pyrolysis process, the thermal breakdown of cellulose, hemicellulose and lignin generates volatile components and the formation of internal pores within the biochar structure, producing microporous and mesoporous structures that increase the overall surface area (Hernandez-Mena et al., 2014).

Furthermore, the methanol-modified bamboo biochar exhibited the highest surface area ( $343.84 \pm 2.14 \text{ m}^2/\text{g}$ ), exceeding the maximum values reported in previous works, suggesting that chemical treatment enhanced the porosity and surface accessibility of the biochar. Solvent modification using polar organic solvents such as methanol can penetrate the carbon structure and remove remaining tar residues or volatile compounds formed during carbonization. This treatment can unblock previously blocked pores and increase the availability of adsorption site on the biochar surface (Li et al., 2014). In addition, chemical modification can introduce oxygen-containing functional groups on the biochar surface, which enhances the adsorption efficiency through mechanism such as surface complexation, electrostatic attraction and pore filling (Li et al., 2014). In contrast, the raw bamboo biomass's low surface area ( $3.88 \pm 0.45 \text{ m}^2/\text{g}$ ) aligns with the lowest values observed in the literature (Wang et al., 2018; Hernandez-Mena et al., 2014), reinforcing the necessity of thermal and/or chemical treatment for surface activation. Raw bamboo is composed of compact lignocellulosic components which are cellulose, hemicellulose and lignin that limits pore accessibility before thermal processing (Hernandez-Mena et al., 2014).

In summary, these findings indicate that slow carbonization followed by methanol modification effectively improves the physiochemical characteristics of bamboo biochar. These treatments produced highly porous materials that shows a promising adsorbent for environmental applications such as wastewater treatment and contaminants removal.



**Figure 2:** SEM images of sample (x2500 magnification): (a) raw bamboo biomass; (b) bamboo biochar; and (c) methanol-modified bamboo biochar at 2500 $\times$  magnification

### 3.4 FESEM analysis

Figure 2 shows SEM micrographs of raw bamboo biomass, bamboo biochar, and methanol-modified bamboo biochar at 2500 $\times$  magnification. As shown in Figure. 2 (a), the raw bamboo biomass exhibits a dense and compact structure with minimal visible porosity which indicates the presence of tightly intact lignocellulosic structures. After undergoing slow carbonization, the bamboo biochar in Figure 2 (b) develops a more porous morphology with clearly visible pore structures formed due to thermal degradation of volatile compounds.

Further modification with methanol improves the surface morphology and produces more accessible active sites. These structural transformations indicate that both slow carbonization and methanol modification contributed to the pore development, which is crucial for high efficiency adsorption for environmental applications.

### 3.5 Surface functional group

The FTIR spectra of raw bamboo, bamboo biochar and methanol-modified bamboo biochar are shown in Figure 3 and Table 4, which highlight the changes in functional group composition caused by slow carbonization and methanol modification. The raw bamboo spectrum exhibited a broad O–H stretching band at  $3337\text{ cm}^{-1}$  representing to hydrogen bonding from hydroxyl groups which is phenols, alcohols and water. Following slow carbonization, this peak disappears which indicates the breakdown of hydroxyl-rich compound such as hemicellulose and cellulose.

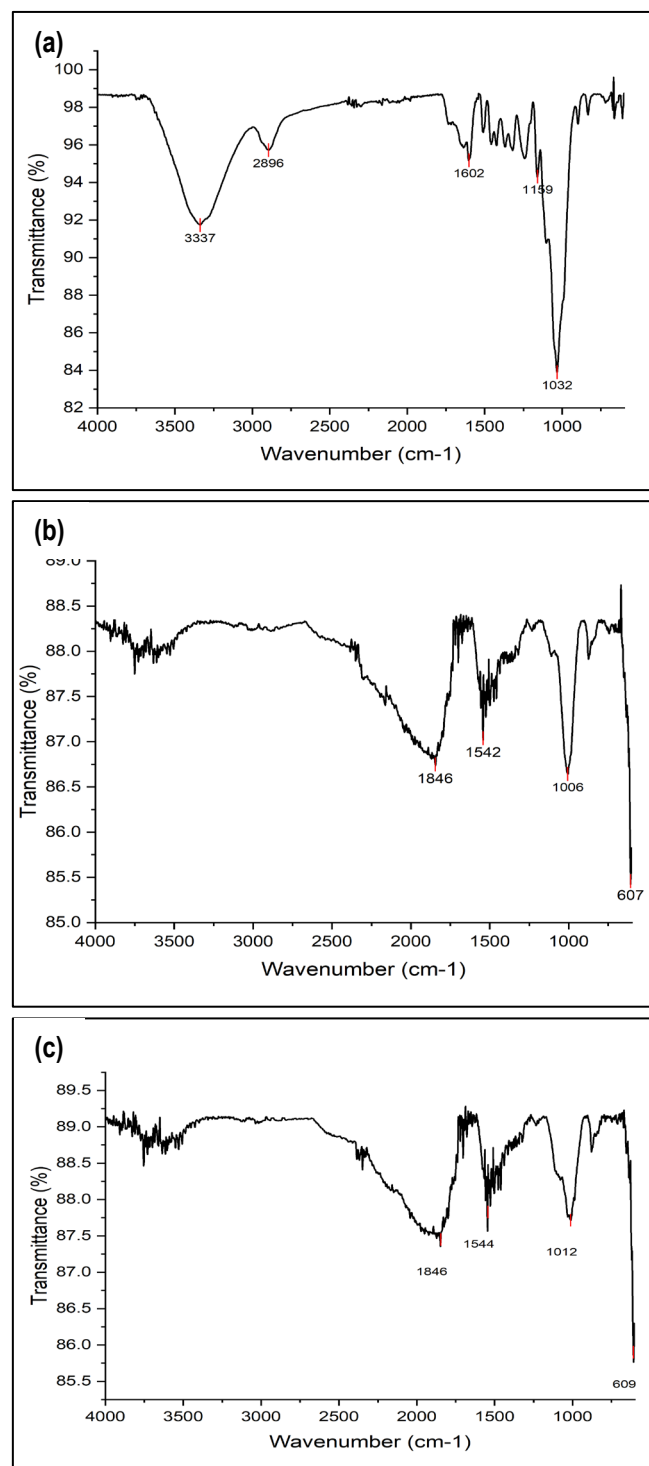
The raw bamboo sample exhibited a sharp to moderate aliphatic C–H stretching peak at  $2896\text{ cm}^{-1}$ , typically attributed to  $-\text{CH}_3$  and  $-\text{CH}_2$  groups from cellulose or lignin. This peak was absent in the spectra for both bamboo biochar and methanol-modified bamboo biochar, which indicates the decomposition of aliphatic chains during carbonization and modification. Furthermore, new peaks appeared in carbonized and methanol-modified samples within the region of  $1850\text{--}1700\text{ cm}^{-1}$ , where C=O stretching peak was observed at  $1846\text{ cm}^{-1}$  for both bamboo biochar and methanol-modified samples. These presence of peaks indicates the formation of carbonyl containing groups such as esters, carboxylic acids and aldehydes, which arise from oxidation during modification.

Within the aromatic region ( $1650\text{--}1500\text{ cm}^{-1}$ ), the raw bamboo shows a C=C stretching band at  $1602\text{ cm}^{-1}$  that indicates to aromatic structures in lignin. The intensity of the peak decreases for bamboo biochar and methanol-modified bamboo biochar but remain detectable at  $1542\text{ cm}^{-1}$ , suggesting that partial preservation of aromatic structures and development of stable polyaromatic structures within the biochar matrix.

As for  $1000\text{--}1100\text{ cm}^{-1}$ , C–O–C linkages and strong C–O stretching at  $1032\text{ cm}^{-1}$  detected in raw bamboo but were substantially reduced after carbonization and methanol modification. These alterations show the breakdown of glycosidic linkages and polysaccharide structures, typically present in cellulose and hemicellulose.

The result obtained from this FTIR analysis confirmed that slow carbonization and methanol modification significantly alter the functional group of the bamboo. The reduction of hydroxyl and aliphatic groups, along with formation of carbonyl and aromatic structures, that improve the stability and surface reactivity of the biochar. The introduction or preservation of oxygen-containing groups,

such as C=O and C–O, is particularly important, as these functionalities are known to enhance adsorption capacity in water treatment applications. Thus, the transformation of functional groups, as seen in Table 4, indicates improved potential of methanol-modified bamboo biochar as an effective adsorbent for environmental remediation.



**Figure 3:** FTIR Spectra for sample: (a) raw bamboo; (b) bamboo biochar; and (c) methanol-modified bamboo biochar

**Table 1:** Proximate analysis of bamboo-based biochar with other studies.

| Sample                                      | Technology         | Reactor                                          | Modifying Agent | Temperature (°C) | Time (min) | Heating Rate (°C/min) | Particle Size (mm) | Moisture (wt.%) | Ash (wt.%)  | Volatile Matter (wt.%) | Fixed Carbon (wt.%) | References                    |
|---------------------------------------------|--------------------|--------------------------------------------------|-----------------|------------------|------------|-----------------------|--------------------|-----------------|-------------|------------------------|---------------------|-------------------------------|
| Raw bamboo ( <i>Dendrocalamus asper</i> )   | -                  | -                                                | -               | -                | -          | -                     | 20 – 50            | 9.48 ± 0.07     | 1.24 ± 0.08 | 77.03 ± 0.60           | 12.65 ± 0.69        | This study                    |
| Bamboo ( <i>Dendrocalamus asper</i> )       | Slow carbonization | Stainless steel reactor enclosed with clay brick | -               | 900              | 300        | -                     | 20 – 50            | 2.29 ± 0.19     | 6.54 ± 0.17 | 33.97 ± 0.80           | 57.13 ± 0.78        | This study                    |
| Bamboo ( <i>Dendrocalamus asper</i> )       | Slow carbonization | Stainless steel reactor enclosed with clay brick | Methanol        | 900              | 300        | -                     | 20 – 50            | 2.10 ± 0.02     | 6.44 ± 0.08 | 32.40 ± 0.45           | 58.88 ± 0.43        | This study                    |
| Bamboo                                      | Pyrolysis          | Muffle furnace                                   | -               | 400 – 600        | 60         | 13                    | 80 – 100           | 1.28 – 4.17     | 2.98 – 4.65 | 10.45 – 9.00           | 81.85 – 83.70       | (Sahoo et al., 2021)          |
| Bamboo ( <i>Phyllostachys heterocycle</i> ) | Pyrolysis          | Fixed bed reactor                                | -               | 400 – 600        | -          | 5                     | < 100              | 1.62 – 2.55     | 1.72 – 9.30 | 10.49 – 37.70          | 58.08 – 78.59       | (Wang et al., 2018)           |
| Bamboo ( <i>D. giganteus Munro</i> )        | Pyrolysis          | Fixed bed reactor                                | -               | 500              | 42 – 72    | 10                    | 0.669              | 6.50            | 3.90        | 8.10                   | 81.50               | (Hernandez-Mena et al., 2014) |

**Table 2:** Ultimate analysis of bamboo-based biochar with other studies.

| Sample                                      | Technology         | Reactor                                                | Modifying Agent | Temperature (°C) | Time (min) | Heating Rate (°C/min) | Particle Size (mm) | Carbon (wt.%) | Hydrogen (wt.%) | Oxygen (wt.%) | Nitrogen (wt.%) | References                    |
|---------------------------------------------|--------------------|--------------------------------------------------------|-----------------|------------------|------------|-----------------------|--------------------|---------------|-----------------|---------------|-----------------|-------------------------------|
| Raw bamboo ( <i>Dendrocalamus asper</i> )   | -                  | -                                                      | -               | -                | -          | -                     | 20 – 50            | 45.18 ± 2.75  | 6.99 ± 1.78     | 47.21 ± 1.22  | 0.63 ± 0.36     | This study                    |
| Bamboo ( <i>Dendrocalamus asper</i> )       | Slow carbonization | Stainless steel brick reactor enclosed with clay brick | -               | 900              | 300        | -                     | 20 – 50            | 71.46 ± 3.89  | 0.98 ± 0.11     | 27.57 ± 3.85  | 0.00            | This study                    |
| Bamboo ( <i>Dendrocalamus asper</i> )       | Slow carbonization | Stainless steel brick reactor enclosed with clay brick | Methanol        | 900              | 300        | -                     | 20 – 50            | 73.68 ± 2.99  | 0.84 ± 0.08     | 25.86 ± 2.71  | 0.00            | This study                    |
| Bamboo                                      | Pyrolysis          | Muffle furnace                                         | -               | 400 – 600        | 60         | 13                    | 80 – 100           | 82.48 – 88.43 | 2.71 – 3.82     | 8.58 – 13.50  | 0.20 – 0.28     | (Sahoo et al., 2021)          |
| Bamboo ( <i>Phyllostachys heterocycle</i> ) | Pyrolysis          | Fixed bed reactor                                      | -               | 400 – 600        | -          | 5                     | < 100              | 72.43 – 82.92 | 2.19 – 4.19     | 5.03 – 21.19  | 0.43 – 0.53     | (Wang et al., 2018)           |
| Bamboo ( <i>D. giganteus Munro</i> )        | Pyrolysis          | Fixed bed reactor                                      | -               | 500              | 42 – 72    | 10                    | 0.669              | 81.50         | 2.72            | 14.60         | 0.54            | (Hernandez-Mena et al., 2014) |

**Table 3:** BET surface area analysis of bamboo-based biochar with other studies.

| Sample                                      | Technology         | Reactor                                                | Modifying Agent | Temperature (°C) | Time (min) | Heating Rate (°C/min) | Particle Size (mm) | S <sub>BET</sub> (m <sup>2</sup> /g) | V <sub>p</sub> (cm <sup>3</sup> /g) | d <sub>p</sub> (nm) | References                    |
|---------------------------------------------|--------------------|--------------------------------------------------------|-----------------|------------------|------------|-----------------------|--------------------|--------------------------------------|-------------------------------------|---------------------|-------------------------------|
| Raw bamboo ( <i>Dendrocalamus asper</i> )   | -                  | -                                                      | -               | -                | -          | -                     | 20 – 50            | 3.88 ± 0.45                          | 0.001 ± 0.001                       | 2.07 ± 1.88         | This study                    |
| Bamboo ( <i>Dendrocalamus asper</i> )       | Slow carbonization | Stainless steel brick reactor enclosed with clay brick | -               | 900              | 300        | -                     | 20 – 50            | 256.75 ± 39.80                       | 0.09 ± 0.05                         | 1.16 ± 0.47         | This study                    |
| Bamboo ( <i>Dendrocalamus asper</i> )       | Slow carbonization | Stainless steel brick reactor enclosed with clay brick | Methanol        | 900              | 300        | -                     | 20 – 50            | 343.84 ± 2.14                        | 0.17 ± 0.02                         | 1.86 ± 0.06         | This study                    |
| Bamboo                                      | Pyrolysis          | Muffle furnace                                         | -               | 400 – 600        | 60         | 13                    | 80 – 100           | 63.52 – 307.10                       | 0.057 – 0.18                        | 2.37 – 3.64         | (Sahoo et al., 2021)          |
| Bamboo ( <i>Phyllostachys heterocycle</i> ) | Pyrolysis          | Fixed bed reactor                                      | -               | 400 – 600        | -          | 5                     | < 100              | 2.18 – 181.05                        | 7.17 – 105.47                       | 2.33 – 13.17        | (Wang et al., 2018)           |
| Bamboo ( <i>D. giganteus Munro</i> )        | Pyrolysis          | Fixed bed reactor                                      | -               | 500              | 42 – 72    | 10                    | 0.669              | -                                    | -                                   | -                   | (Hernandez-Mena et al., 2014) |

**Table 4:** FTIR spectra of raw bamboo, bamboo biochar and methanol-modified bamboo biochar

| Wavenumber Range (cm <sup>-1</sup> ) | Functional Group               | Raw Bamboo                                               | Bamboo Biochar                     | Methanol-modified Bamboo Biochar   | Surface Functional Group/Assignments                                                    |
|--------------------------------------|--------------------------------|----------------------------------------------------------|------------------------------------|------------------------------------|-----------------------------------------------------------------------------------------|
| 3700 - 3200                          | O-H Stretching                 | Broad peak at 3336 cm <sup>-1</sup>                      | Absent                             | Absent                             | Hydrogen bonding (alcohols, phenols, water)                                             |
| 3000 - 2850                          | C-H Stretching (aliphatic)     | Sharp to medium intensity peak at 2893 cm <sup>-1</sup>  | Absent                             | Absent                             | Aliphatic -CH <sub>3</sub> and -CH <sub>2</sub> group from cellulose/ lignin            |
| 1850 - 1700                          | C=O Stretching                 | Absent                                                   | Peak in 1846 cm <sup>-1</sup>      | Peak in 1846 cm <sup>-1</sup>      | Carbonyl groups: carboxylic acids, ester, aldehydes                                     |
| 1650 - 1500                          | C=C Stretching (aromatic ring) | Medium to strong intensity at 1602 cm <sup>-1</sup>      | Weak peak at 1542 cm <sup>-1</sup> | Weak peak at 1544 cm <sup>-1</sup> | Aromatic rings in lignin                                                                |
| 1180 - 1140                          | C-O-C stretching               | Medium to strong intensity peak at 1159 cm <sup>-1</sup> | Absent                             | Absent                             | Glycosidic linkages in cellulose / hemicellulose; decomposed after pyrolysis            |
| 1100 - 1000                          | C-O Stretching                 | Strong peak at 1032 cm <sup>-1</sup>                     | Weak peak at 1006 cm <sup>-1</sup> | Weak peak at 1012 cm <sup>-1</sup> | Polysaccharide backbone in cellulose / hemicellulose; typically lost in thermal process |

#### 4. CONCLUSION

This study successfully demonstrated that raw bamboo which underwent slow carbonization at 900 °C for 5 h using a stainless-steel brick reactor enclosed with clay brick layer, followed by a 24-hour methanol modification, significantly enhanced the physicochemical and surface properties of the resulting biochar. BET surface area significantly increased from 3.88±0.45 m<sup>2</sup>/g in raw bamboo to 256.75±39.80 m<sup>2</sup>/g after slow carbonization and further increased to 343.84±2.14 m<sup>2</sup>/g after methanol treatment. SEM analysis confirmed the formation of well-developed porous structures, and FTIR analysis revealed the presence of active surface functional groups such as carbonyl and aromatic structures. This study demonstrates that combination of slow carbonization and methanol modification can improve the structural, surface and physiochemical characteristics of bamboo derived biochar. Furthermore, the stainless-steel brick reactor covered with clay bricks layer which provides a stable and efficient carbonization system which ensures a uniform heat transfer, and consistent thermal degradation of biomass. Such a reactor design provides a practical and energy-efficient method to produce a good quality biochar. These improvements in terms of surface area after methanol modification show a strong potential of methanol-modified bamboo biochar for various environmental applications. The carbonization and chemical modification approach from this study can be applied to various lignocellulosic feedstock for production of high-quality biochar products. Compared to conventional biochar production approaches, this method offers simple and cost-effective techniques for enhancing biochar quality and as energy-efficient alternatives. Thus, overall results contribute to development of sustainable

biochar production technologies and shows the ability to efficient adsorbent for environmental applications.

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