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RESEARCH ARTICLE

COMPARATIVE PHYSICOCHEMICAL PROPERTIES OF BAMBOO-DERIVED ACTIVATED CARBONS FOR WASTEWATER TREATMENT APPLICATION

Che Nor Aiza Jaafar[1,*], Charles Christopher Sorrell[2], Nur Asma Izni Ruslan[1], Ismail Zainol[3]

[1]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43000 Serdang Selangor, Malaysia.*

[2]*School of Materials Science and Engineering, Hilmer Building (E10), University New South Wales, Sydney, New South Wales, 2052, Australia.*

[3]*Department of Chemistry, Faculty of Science and Mathematics, Universiti Pendidikan Sultan Idris, Proton City, 35900 Tanjung Malim, Perak, Malaysia.*

Abstract. Activated carbon (AC) is widely used in wastewater treatment due to its large surface area and pore volume, which enable efficient contaminant removal. Considerable research has focused on producing cost-effective AC from low-cost raw materials using physical or chemical activation methods. Chemical activation is generally preferred because it promotes the formation of larger pore structures and requires lower activation temperatures. In this study, three bamboo species: *Bambusa vulgaris* (BV), *Gigantochloa scortechinii* (GS), and *Schizostachyum brachycladum* (SB) were used to produce bamboo-based activated carbon (BAC) using sodium chloride (NaCl) as the activating agent. The physicochemical properties of the BAC produced through different activation procedures were compared, with activation carried out either before or after carbonization at room temperature. The influence of activation sequence on BAC properties was evaluated using density, porosity, iodine number, methylene blue adsorption, and scanning electron microscopy (SEM) analyses. The results showed that NaCl treatment significantly enhanced the iodine number of all bamboo-derived AC, achieving values within the commercial range (861–950 mg/g), along with high methylene blue adsorption capacities (384-441 mg/g). The activation procedures (before or after carbonization) did not markedly affect overall BAC performance. Among the tested species, *Bambusa vulgaris* activated after carbonization (ABV) exhibited the highest bulk density (0.29-0.40 g/cm^3), porosity (73.59-83.71 %), iodine number (950 mg/g), and methylene blue adsorption capacity (441 mg/g). SEM images revealed that all bamboo-derived AC samples displayed porous structures under both activation procedures, confirming that ABV-based BAC possessed the most well-developed porosity. These findings demonstrate that NaCl-assisted chemical activation effectively produces high-quality BAC from bamboo, offering a sustainable and economical adsorbent suitable for wastewater treatment applications.

Keywords: Activated carbon (AC), NaCl chemical activation, bamboo, porosity, iodine number.

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***Corresponding author: cnaiza@upm.edu.my**

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1. INTRODUCTION

Currently, the discharge of heavy chemical waste from factories, construction sites, and chemical industries into the environment polluted water and become a major concern. This issue has driven the development of various wastewater treatment technologies. Among these, adsorption has shown high efficiency in removing both organic and inorganic contaminants in wastewater. Numerous researchers have investigated alternative approaches to develop cost-effective adsorbent materials for water treatment [1,2] Activated carbon (AC) has been widely reported as the most commonly used adsorbent for eliminating micropollutants from water treatment systems [3-5]

Activated carbon (AC), a material primarily composed of elemental carbon, is an excellent adsorbent for removing chemical compounds from stream water due to its large pore volume and extensive surface area [6]. Beyond water treatment applications, AC is also widely utilized in various fields such as supercapacitors, battery electrodes, and catalytic supports [5,7]. Owing to its high surface area and well-developed pore structure, AC is considered an efficient and versatile material for reducing energy consumption and mitigating environmental challenges [5]. The adsorption capacity of activated carbon (AC) primarily depends on its structural characteristics, particularly its porous properties such as pore width, pore size distribution, and surface area [8,9].

AC can be produced from various industrial waste materials using two primary activation process: physical activation and chemical activation processes. In physical activation, temperatures typically range from 800 to 1100 °C and the process involves the use of activating agents such as steam, oxygen (O_2), or carbon dioxide (CO_2). In contrast, chemical activation entails treating the carbonaceous precursor with alkaline reagents such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) or acidic chemicals including zinc chloride ($ZnCl_2$), sodium chloride (NaCl), phosphoric acid (H_3PO_4) and sulfuric acid (H_2SO_4) as activating agents [1,2,10,11].Chemical activation process is generally preferred in industrial applications because it requires lower activation temperatures (typically below 800 °C), shorter processing times while producing activated carbon with a higher yield, cheap and well-developed porous structure [11,12]. The physicochemical properties of the resulting activated carbon are determined by various factors, such as the type of the activating agent, surface area, concentration of the chemical activating agent, pore volume, activation time and processing temperature [13].

Bamboo is considered a promising alternative precursor for AC production due to its abundance, versatility, and low cost. It is also regarded as a renewable resource because of its rapid growth rate and wide availability in Malaysia. The most common bamboo species that has potential for bamboo-based activated carbon (BAC) production include *Bambusa vulgaris, Gigantochloa scortechinii, Gigantochloa levis, Gigantochloa ligulata, Dendrocalamus asper, Bambusa blumeana, Schizostachyum grande*, and *Schizostachyum zollingeri.* Examples of bamboo species found in Malaysia is shown in Figure 1. The utilization of bamboo can help industries generate income from an otherwise underutilized natural resource.

Bamboo activated carbon (BAC) can be produced through either physical or chemical activation methods. In this study, chemical activation was selected because it enables optimization of the adsorption properties by promoting the formation of larger pore diameters, thereby producing BAC that serves as an efficient adsorbent for wastewater treatment applications [14]. The potential of sodium chloride (NaCl) as an activating agent was investigated using three different bamboo species. Only a few studies have explored the potential of NaCl as a chemical activating agent, as it is non-toxic, inexpensive, and readily available compared to conventional activating chemicals. Furthermore, the effects of chemical treatment procedures before and after carbonization have not been reported; therefore, this study aims to examine the differences in the quality of AC produced from bamboo under these conditions.

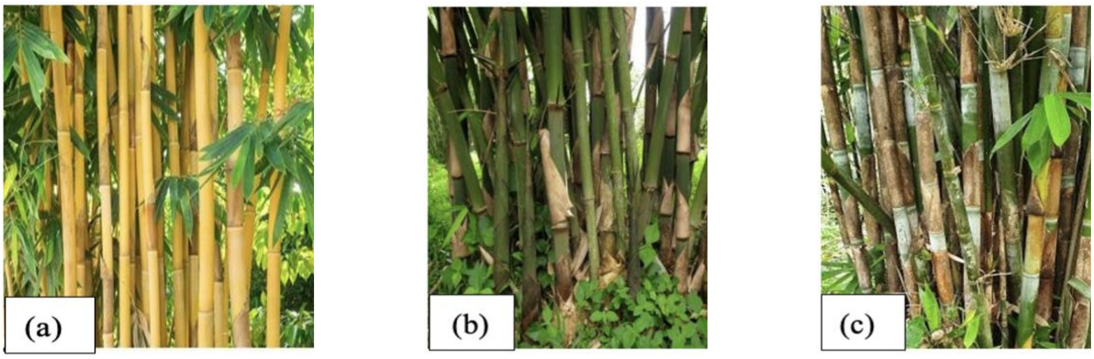

Figure 1: Examples of bamboo species found in Malaysia (a) *Bambusa vulgaris* (BV), (b) *Gigantochloa scortechinii* (GS) and (c) *Schizostachyum brachycla* (SB)

2. MATERIALS AND METHODS

In this study, locally sourced bamboo was used as the raw material to produce bamboo activated carbon (BAC). Three bamboo species were utilized: *Bambusa vulgaris* (BV), locally known as Buluh Kuning; *Gigantochloa scortechinii* (GS), locally known as Buluh Telur; and *Schizostachyum brachycladum* (SB), locally known as Buluh Lemang. The bamboo samples were collected from Setiu, Terengganu, Malaysia. The cross-sectional structures of these bamboo species are shown in Figure 2. Among the three species, BV exhibits the thickest wall, followed by GS and SB. Sodium chloride (NaCl) was employed as the chemical activating agent.

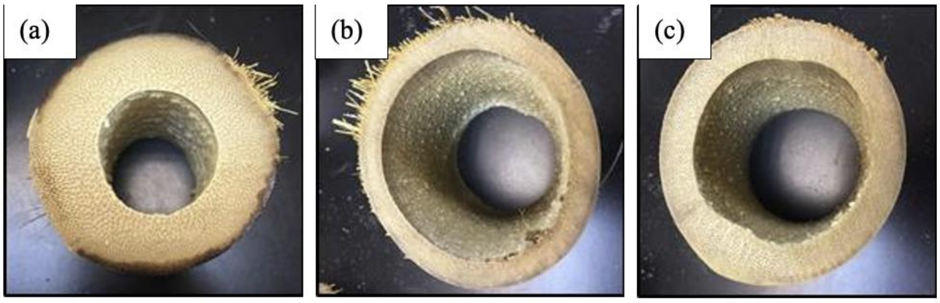

Figure 2: Cross-section area of different bamboo species: (a) *Bambusa vulgaris* (BV) (b) *Gigantochloa scortechinii*and (GS) and (c) *Schizostachyum brachycladum* (SB)

2.1 Sample Preparation

Initially, the raw three bamboo was dried in a universal oven at 85 °C for 24 hours to remove moisture and residual water content. The dried bamboo was then cut using a cutting machine (CF2300 Okatz High-Speed Cutter Chop-Off Saw) to form 'O' ring to facilitate uniform grinding and to obtain short fibres of consistent size. Subsequently, the 'O' ring bamboo pieces were manually reduced in size using a hammer and then ground with mechanical grinder to obtained approximately 2.0 mm long bamboo fibrous granules.

2.2 Activation Process and Carbonization

25 % NaCl solution was employed as the chemical activating agent to impregnate the bamboo fibrous granules. Two activation procedures were conducted. In the first, the bamboo granules were impregnated with 25 % NaCl for 24 hours at room temperature (RT) prior to carbonization at 800 °C for 1 hour (before carbonization). In the second, the samples were carbonized at 800 °C for 1 hour at a

heating rate of 10 °C/min to produce biochar, then activated with 25 % NaCl for 24 hours at RT (after carbonization). The impregnation ratio was 2:1 (NaCl solution:sample mass weight). Following activation, the samples were rinsed repeatedly 3 times with distilled water, oven-dried at 100 °C for 1 hour prior to further analyses. The labeling of the activated carbon (AC) bamboo samples is summarized in Table 1.

Table 1: Types of activation procedure, bamboo species, and labeling of bamboo-activated carbon

Activation Procedure	Species	Coding	Label
Before Carbonization	*Bambusa Vulgaris* (Buluh Kuning)	BV	BBV
	GigantochloaScortechinii (Buluh Telur)	GS	BGS
	Schizostachyum Brachycladum (Buluh Lemang	SB	BSB
After Carbonization	*Bambusa Vulgaris* (Buluh Kuning)	BV	ABV
	GigantochloaScortechinii (Buluh Telur)	GS	AGS
	Schizostachyum Brachycladum (Buluh Lemang	SB	ASB

2.3 Density and Porosity Analyses

Two types of densities were evaluated in this study: bulk and true density. The bulk density of the BAC was determined using a density analyzer (Model: Micromeritics GeoPyc 1360). The analysis was conducted using a graduated cylinder mounted on a vertical compaction device. The true density of the BAC was measured using a pycnometer. Based on both measurements, the porosity of each sample was calculated using Equation (1). The test was conducted in triplicate and average values are reported.

$$\text{Porosity} = 1 - \frac{\text{Bulk density}}{\text{True density}} \text{ x } 100\% \tag{1}$$

2.4 Iodine Number Analysis

The determination of the iodine number of activated carbon (AC) was carried out in accordance with the ASTM D4607-94 standard test method [15]. The iodine number serves as a relative indicator of porosity and provides an approximate measure of the surface area of AC, including BAC. For the analysis, about 10 mL of 5 wt% hydrochloric acid (HCl) solution was pipetted into an Erlenmeyer flask containing 0.9–1.0 g of powdered BAC. Subsequently, 100 mL of standard iodine (I_2) solution was added, and the mixture was shaken vigorously for approximately 30 seconds. The resulting suspension was immediately filtered through folded filter paper into a measuring cylinder. The first 20 mL of the filtrate was discarded, and the next 50 mL was collected for analysis. The filtrate was titrated with a sodium thiosulfate ($Na_2S_2O_3$) solution until a pale-yellow color appeared. Then, 2 mL of starch indicator solution was added, producing a blue-black coloration. Titration was continued until the solution turned colorless with the addition of one final drop of $Na_2S_2O_3$ solution. The iodine number (I_n) for each sample was calculated using Equation (2).

$$I_n = \frac{N_2 \text{ x } 12693.0 - (DF)(N_1 - 126.93)(S)}{M} \tag{2}$$

where N_1 is the normality of the sodium thiosulfate ($Na_2S_2O_3$) solution, N_2 is the normality of the iodine (I_2) solution, DF is the dilution factor, S is the volume of sodium thiosulfate solution used (mL), and M is the mass of the activated carbon sample (g). The analysis was conducted in triplicate and average values were reported.

2.5 Methylene Blue Analysis

The adsorption of methylene blue (MB) is commonly employed to characterize activated carbon (AC) in terms of pore distribution and adsorption capacity [16]. The absorbance of the MB solution was measured using a UV–visible spectrophotometer (Cary 60 model) at a wavelength of 664 nm, corresponding to the maximum absorption peak of MB. The MB concentration was determined from a calibration curve correlating solution concentration with absorbance. By measuring the absorbance of the dye solution before and after adsorption, the amount of MB adsorbed, q (mg/L), was calculated using Equation (3).

$$q = \frac{(C_i - C_f)(V)}{m} \tag{3}$$

where C_i and C_f represent the initial and final dye concentrations in the liquid phase (mg/L), respectively, meanwhile V is the volume of the adsorbate solution (L) and m is the mass of the adsorbent (g). The analysis was conducted in triplicate and average values were reported.

2.6 Microstructural Analysis

A field electron scanning electron microscope (Model: JSM 6400), operated at an accelerating voltage of 2 kV was used to analyse the pore structure and surface morphology of the produced BAC samples. SEM analysis effectively reveals the surface features and microporous structure of BAC, providing ultra–high-resolution images at low accelerating voltages that enable detailed examination of the top surfaces of nano powders. Prior to analysis, the samples were coated with a thin layer of gold to prevent surface charging and to enhance electrical conductivity.

3. RESULTS AND DISCUSSION

3.1 Density and Porosity of Bamboo-based Activated Carbon

True density refers to the density of the solid material and represents the mass per unit volume excluding any pore spaces within the sample. Generally, the true density value is higher than the bulk density because it reflects only the solid portion of the material, without accounting for porosity. The true density results for the three BAC from different species under both activation procedure are presented in Figure 3. The true density results indicate that bamboo samples treated under both procedures exhibited higher true density values than the untreated samples (UT). This finding contrasts with the work of Tan et al. (2023), who reported that salt-assisted carbonization generally promotes porosity and increases surface area rather than producing a denser or more tightly packed carbon structure [17]. The observed increase in true density may therefore be attributed to the formation of closed or isolated pores that are inaccessible to the water medium used in the liquid pycnometer technique, leading to an underestimation of pore volume and a corresponding rise in apparent density. Additionally, incomplete removal of NaCl or residual ash may have artificially elevated the measured density values.

The effect of sodium chloride (NaCl) treatment on the characteristics of bamboo-based activated carbon (BAC) varied significantly depending on whether the treatment was applied before or after carbonization. When NaCl was introduced before carbonization**,** it acted as a chemical activating agent that promoted the decomposition of the bamboo's lignocellulosic components, resulting in the formation of a more porous carbon structure [9]. During pyrolysis, the presence of NaCl facilitated the release of volatile matter and created additional pore sites; however, this also produced a carbon matrix with a lower true density due to the higher internal void volume and less compact carbon framework.

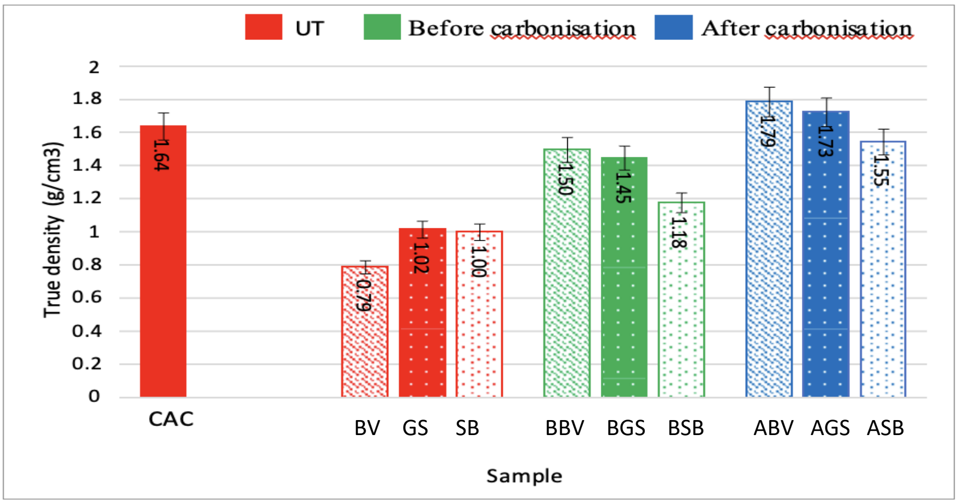

Figure 3: The effects of activation proceduer before and after carbonization process on true density of different bamboo species

In contrast, NaCl treatment after carbonization led to an increase in the true density of the BAC. In this case, the salt solution penetrated the existing pores and assisted in removing residual impurities, tar, and inorganic matter while promoting a slight reorganization or compaction of the carbon microstructure. This post-treatment resulted in a cleaner and denser carbon matrix with reduced microvoids and higher atomic packing efficiency. Consequently, while pre-carbonization NaCl treatment primarily enhanced porosity and surface development, post-carbonization treatment improved the structural compactness and true density of the bamboo activated carbon. These observations are in line with previous studies on salt-activated bio-chars and activated carbons that highlight how chemical impregnation and subsequent heat treatment influence pore structure and carbon skeleton integrity [17-19]. Among the bamboo species, ABV showed the highest true density values 1.79 g/cm^3 followed by AGS 1.73 g/cm^3 and ASB 1.55 g/cm^3, respectively as compared to the untreated bamboo samples and treated bamboo before carbonization process. It can be concluded that BV exhibited the highest true density, consistent with its thicker wall structure (Figure 2)**.**

The bulk density of AC is defined as the mass of AC particles divided by the total volume they occupy, which includes the particle volume, inter-particle voids, and internal pore volume. In general, a lower bulk density indicates greater porosity development within the BAC samples. Figure 4 presents the bulk density results for the three BAC activated at room temperature. Overall, the NaCl-treated BAC samples exhibited lower bulk density values compared to the untreated sample (UT). The lowest bulk density observed across all three bamboo species indicates a higher void fraction within the granules, attributed to enhanced pore development during the chemical activation process with NaCl.

As shown in Figure 4, the bulk density values of the treated samples (both before and after carbonization) were lower than those of the untreated samples, including the commercial activated carbon (CAC) sample. Among the bamboo species, BV exhibited the lowest bulk density, with values of 0.40 g/cm^3 for the activation process before carbonization and 0.29 g/cm^3 for the activation process after carbonization. In contrast, AGS and ASB recorded bulk density values of approximately 0.45 g/cm^3 after carbonization at 800 °C followed by chemical activating with NaCl at room temperature.

The lowest bulk density observed in ABV indicates that the sample, after carbonization and activation, possessed the highest void fraction within the BAC granules. This finding confirms that the ABV species developed a greater degree of porosity, as reflected by its lower bulk density value. When compared with the commercial activated carbon (CAC), the untreated (UT) samples exhibited similar bulk density results to CAC. This suggests that NaCl as chemical activating reagent has played a crucial role in promoting cavity formation and enhancing the internal pore structure of BAC under both activation procedure [14,17].

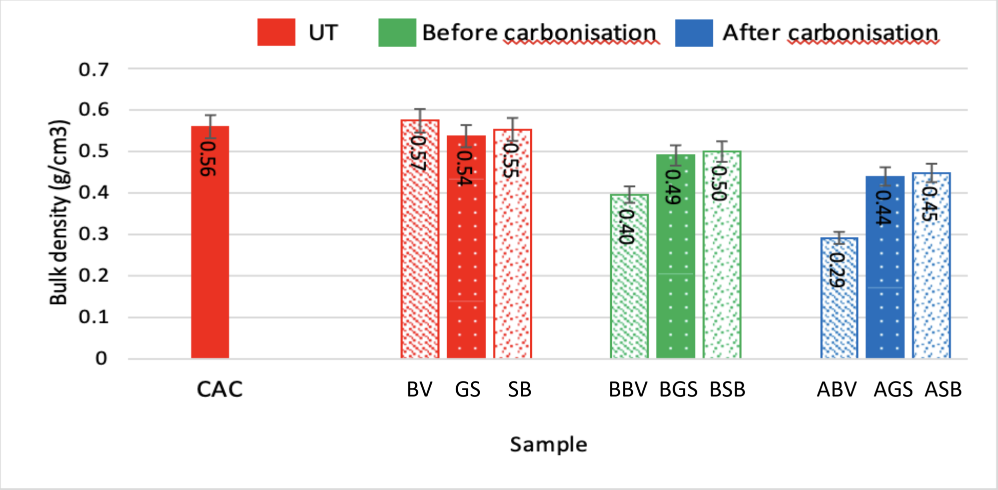

Figure 4: The effect of activation process before and after carbonization process on bulk of different bamboo species

Based on bulk and true density values, the porosity of all samples was calculated using Equation (1) and the results were plotted as shown in Figure 5. All untreated (UT) bamboo samples exhibited the lowest porosity values, ranging from 27 % to 47 %, compared to the NaCl-treated samples. This can be attributed to the absence of chemical activation in the UT samples, which limited pore development and consequently resulted in lower porosity values.

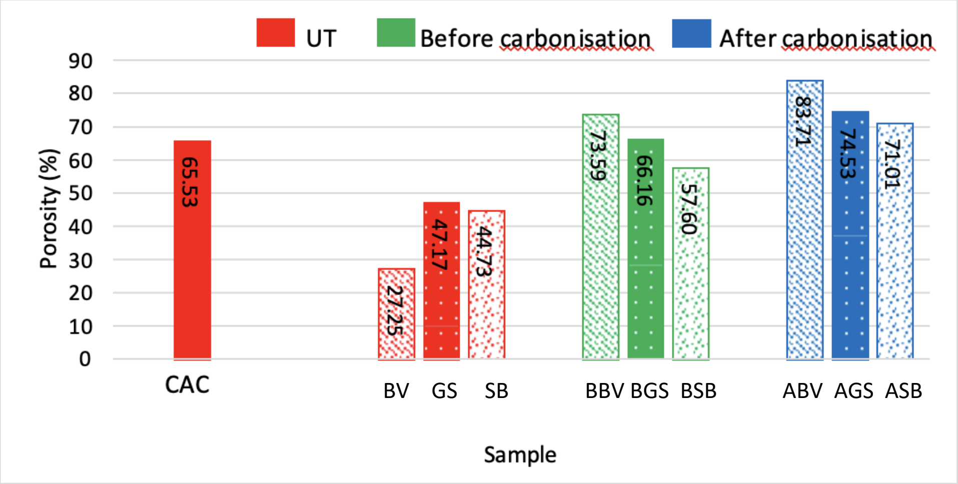

Figure 5: The effect of activation process before and after carbonization procedure on porosity of BAC from different bamboo species

When comparing the two activation procedures, the bamboo samples activated after the carbonization process exhibited higher porosity values than those activated before carbonization. Among BAC samples, bamboo species ABV exhibited the highest porosity followed by AGS, ASB and CAC. The samples treated with NaCl demonstrated a significant increase in porosity under both activation conditions, confirming that chemical activation effectively enhanced pore development in the bamboo-derived activated carbon [11,14]. Since density and porosity directly affect the adsorption quality and performance of activated carbon, the subsequent iodine number analysis is essential.

3.2 Iodine Number Analysis

The iodine number is a critical parameter for assessing the performance of activated carbon, as it indicates the extent of pore development and provides an indirect measure of micropore content and surface area. Ismail et al. [14] reported that activated carbon suitable for water and wastewater treatment typically exhibits iodine numbers in the range of 600–1100 mg/g. Higher iodine values signify a more developed microporous structure and, consequently, greater adsorption capacity for small molecules, enhancing suitability for purification applications. The iodine number results for the different bamboo-based activated carbon (BAC) species subjected to activation before and after carbonization are presented in Figure 6.

The BAC samples displayed iodine numbers ranging from 861 to 950 mg/g across both activation procedures. The highest value, 950 mg/g, was recorded for ABV chemically activated with NaCl after carbonization, which aligns with its superior porosity (83.71 %). Similarly, BBV activated with NaCl prior to carbonization achieved a high iodine number of 923 mg/g, surpassing that of the commercial activated carbon (CAC) sample (819 mg/g). These results demonstrate that both activation approaches successfully produced BAC with well-developed pore structures, as evidenced by the elevated iodine values. Such high iodine numbers indicate extensive micropore formation, which is associated with improved adsorption of small contaminants and enhanced filtration efficiency. Furthermore, the inherently high carbon content and the presence of abundant fibrovascular bundles in bamboo facilitate the development of a porous carbon framework, contributing to its excellent adsorptive properties, as noted by Samarawickrama et al. [20].

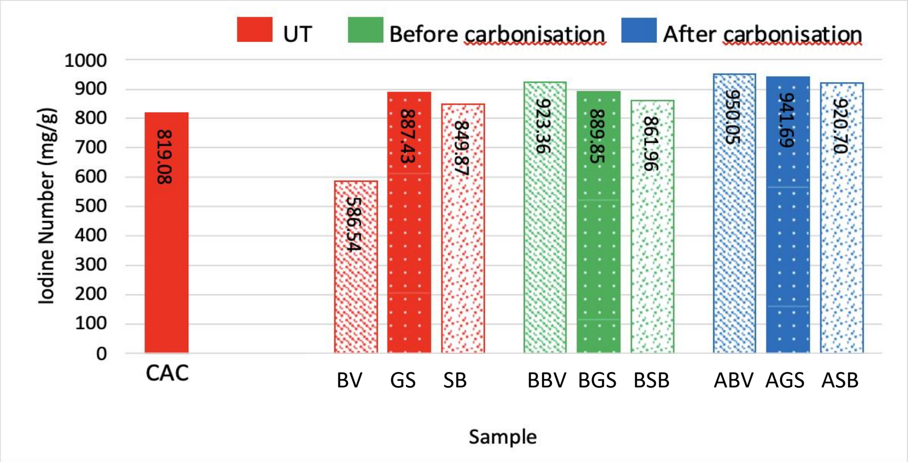

Figure 6: The effect of bamboo activated before and after carbonization procedure on iodine number

3.3 Methylene Blue Analysis

To evaluate the adsorption capacity, a methylene blue (MB) adsorption test was conducted on the BAC. This test is closely associated with the development of mesopores and macropores, as the MB molecules are predominantly adsorbed within these pore regions of the AC [21]. Figure 7 illustrates the amount of MB adsorbed by BAC from BV, GS and SB species for both activation procedures: before and after the carbonization process compared with the untreated (UT) bamboo samples and commercial activated carbon (CAC). It was also observed that the methylene blue (MB) adsorption capacities of all NaCl-treated bamboo samples were higher than those of the commercial activated carbon (CAC) and untreated (UT) samples. The highest methylene blue adsorption capacity was recorded for the ABV sample at 441 mg/g, followed closely by BBV with 434 mg/g. These results indicate that chemical activation with sodium chloride (NaCl) significantly improves the pore structure of bamboo-based activated carbon (BAC), regardless of whether activation is performed before or after carbonization. A similar pattern was observed across all three bamboo species. In general, a higher MB adsorption capacity indicates a greater distribution of mesopores within the bamboo AC structure. The methylene blue (MB) adsorption results were consistent with the findings from the porosity and iodine number analyses, both of which showed higher values for the samples activated after the carbonization process across all bamboo species. Similar observation was reported by Kanuengit & Mudjalin [17].

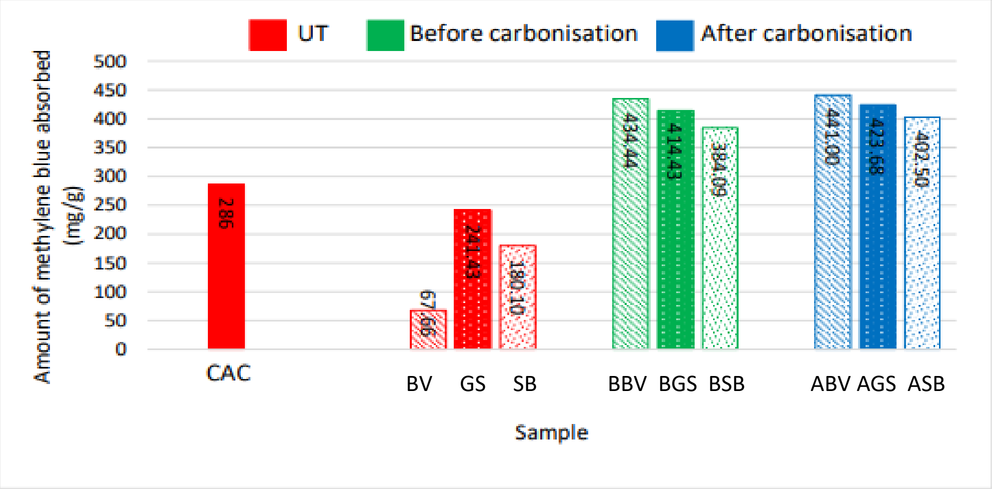

Figure 7: The amount of MB absorbed of samples for both activation before and after carbonization procedures

3.4 Morphology Properties

To support the analysis of textural characteristics, SEM analysis was conducted to observe the surface morphology of untreated bamboo and optimized BAC samples prepared under room temperature activation for 24 hours. The morphological features of the different bamboo species under untreated conditions and two activation procedures are presented in Figures 8 to 10. In this analysis untreated BV precursor exhibited a relatively smooth surface with limited visible pores and thick fibrovascular bundle walls, likely due to the agglomeration of condensable volatile compounds on the carbon surface. In contrast, numerous pores of various shapes and sizes were clearly observed on the BAC surfaces after treatment with 25 wt% NaCl for both activation procedures, particularly in the BV sample activated after the carbonization process ((Figures 8(b) and 8(c)).

The large and well-developed pores observed in the ABV and BBV species contributed to a larger surface area and a more porous structure of the BAC, which is consistent with the results of bulk density, porosity, iodine number, and methylene blue analyses. The formation of pore structures within the fibrovascular bundle walls after activation facilitates faster diffusion of contaminants into the AC [22]. Therefore, based on the SEM analyses, it can be concluded that both activation procedures employed in this study are effective for producing bamboo-derived activated carbon suitable for water filtration applications.

It can be observed that in the inactivated GS sample ((Figure 9(a)), the fibrovascular bundle walls appear thicker compared to the treated samples. However, after the activation process, a considerable number of pore structures were detected on the surfaces of both treated samples, as shown in Figures 9(b), BGS and Figure 9(c), AGS. The pores visible on the surface are likely macropores that branch into micropores within the interior of the activated carbon. These findings indicate that the formation of pore structures resulted from the partial destruction of cell walls during the activation process with NaCl as the activating agent [23].

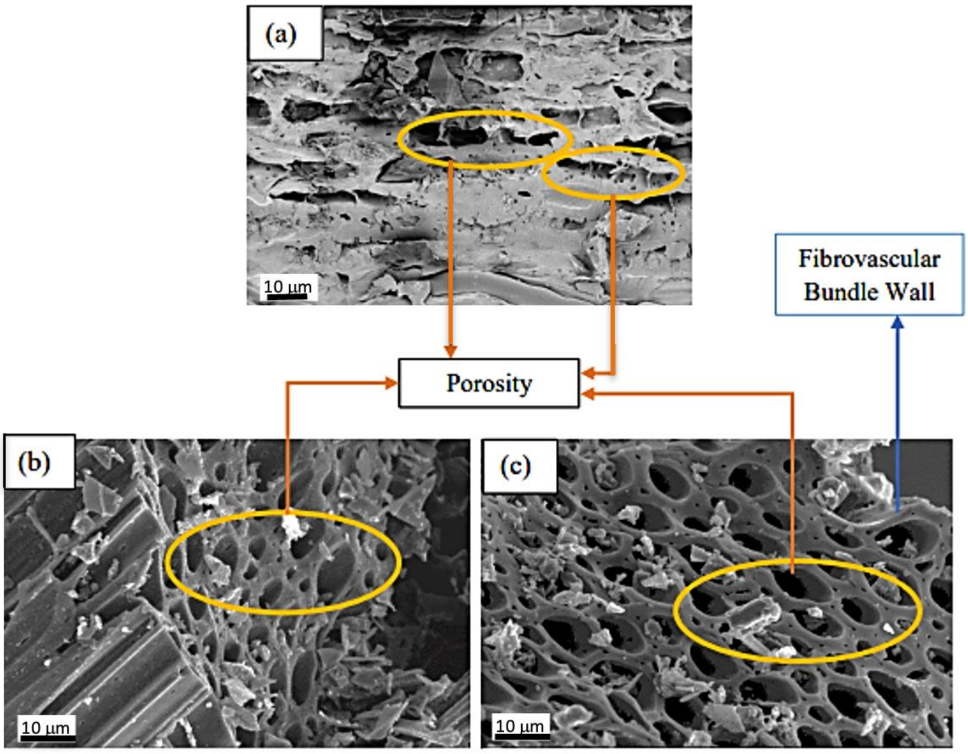

Figure 8: SEM micrographs of *Bambusa vulgaris* (BV) bamboo species: (a) untreated sample, (b) sample activated before carbonization (BBV), and (c) sample activated after carbonization (ABV)

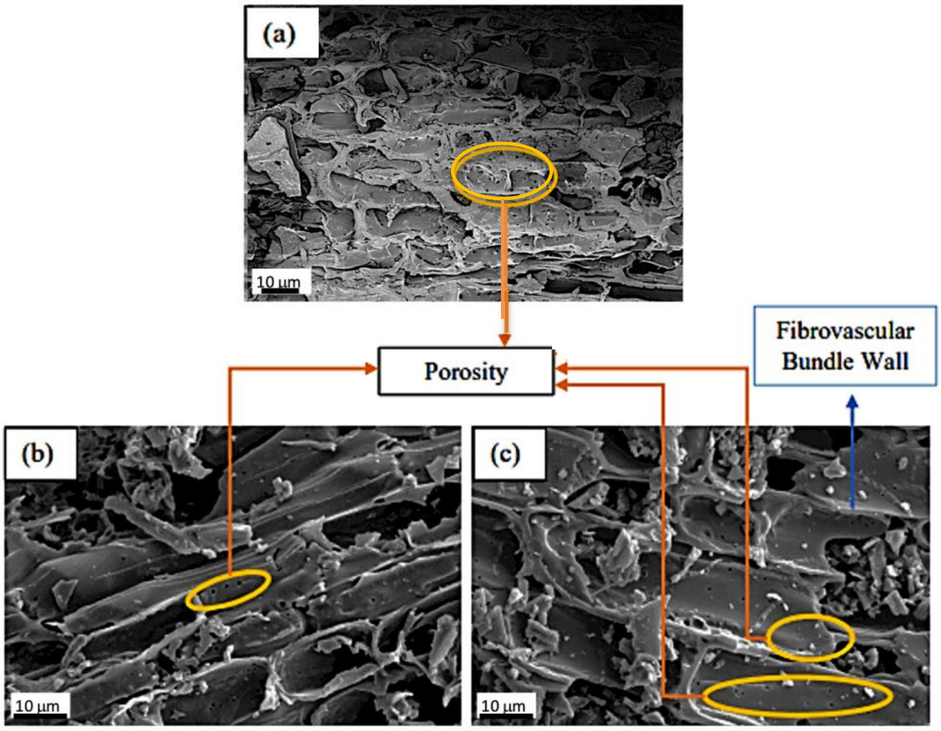

Figure 9: SEM micrographs of *Gigantochloa scortechinii* (GS) bamboo species: (a) untreated sample, (b) sample activated before carbonization (BGS), and (c) sample activated after carbonization (AGS)

Figure 10 shows SEM micrographs of SB bamboo species for untreated sample, sample activated before carbonization (BSB), and sample activated after carbonization (ASB). As shown in Figure 10(a), the surface structure of the BAC derived from SB retained the characteristic fibrovascular bundle structure of the raw bamboo. The surface appeared relatively smooth with limited cavities and pores. The effect of using NaCl as the activating agent in the production of BAC is evident in Figures 10(b) and 10(c), where a more porous surface structure was observed. The activated samples exhibited rougher surfaces, greater pore irregularity, and thinner fibrovascular bundle walls. The presence of the activating agent facilitated the enlargement of pores and the expansion of the surface area [22]. Overall, when comparing the micrographs of the three bamboo species, BV species displayed the most well-developed pores, a wider pore structure, and thinner fibrovascular bundle walls compared to GS and SB species.

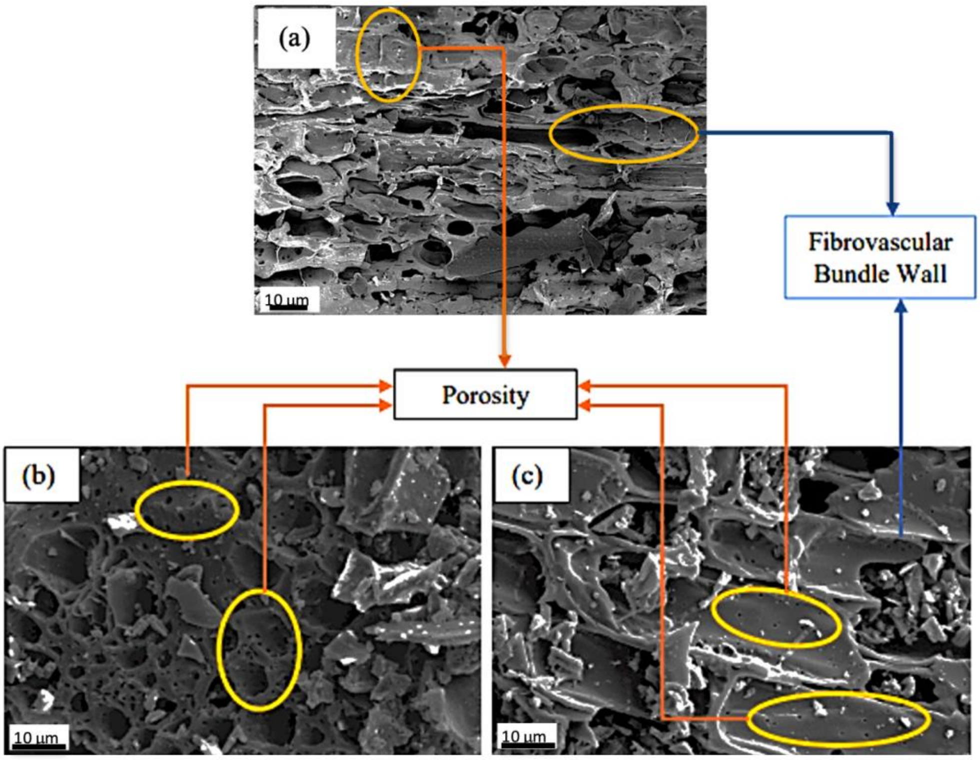

Figure 10: SEM micrographs of Schizostachyum brachycladum (SB) bamboo species: (a) untreated sample, (b) sample activated before carbonization (BSB), and (c) sample activated after carbonization (ASB)

4. CONCLUSIONS

This study demonstrated that activation of three bamboo species with 25 wt% NaCl effectively produced high-quality bamboo activated carbon (BAC) with superior adsorption characteristics compared to both untreated samples and commercial activated carbon (CAC). The activated samples exhibited increases in porosity, iodine number, and methylene blue adsorption of 32, 62 and 557 %, respectively, relative to the untreated materials. Among the bamboo species investigated, *Bambusa vulgaris* (BV) activated after carbonisation showed the best performance, achieving the highest iodine number (950 mg/g) and methylene blue adsorption capacity (441 mg/g). Scanning electron microscopy analysis further revealed that BV-derived BAC possessed a well-developed pore structure, larger pore sizes, and thicker fibrovascular bundle walls, confirming its superior textural properties compared to the other species. The superior performance of BV is attributed to its dense vascular structure, which facilitates extensive pore formation during NaCl activation. Overall, BV species activated after carbonisation demonstrated strong potential as a renewable and cost-effective precursor for producing high-performance activated carbon suitable for wastewater treatment applications.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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