Charcoal Properties of Malaysian Bamboo Charcoal Carbonized at 750 °C

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The carbonization of five Malaysian bamboo species, namely *Bambusa vulgaris, Dendrocalamus asper, Gigantochloa hasskarliana, Gigantochloa levis*, and *Schizostachyum brachycladum*, was conducted to investigate the charcoal properties and compare the quality of bamboo charcoal produced based on proximate analysis. Carbonization at 750 °C using a modified Iwasaki steel drum kiln was successful for all bamboo species. Bamboo morphological features varied and basic density increased with culm height. A charcoal yield of more than 30% was recorded in all bamboo species except for *B. vulgaris* and *D. asper*. Charcoals made from *D. asper* and *G. hasskarliana* could serve as the alternative raw material for charcoal production in charcoal industries due to their low moisture, low volatile matter, low ash, and high fixed carbon content. All species had a mean gross calorific value between 24.4 and 29.2 MJ/kg. Among different culm sections, the bottom section produced the best quality charcoal. The charcoal quality from all species was of acceptable quality for domestic use.

DOI: 10.15376/biores.18.3.4413-4429

Keywords: Carbonization; Bamboo charcoal; Steel drum kiln; Proximate analysis; Charcoal quality

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INTRODUCTION

Bamboo is among the earliest raw materials utilized by humankind for various purposes, and it is classified under non-timber forest products. With a total of 1,642 species belonging to 123 genera (Vorontsova *et al*. 2016), approximately 3.2% of the world's total forest area is covered with bamboo. In 2019, global bamboo production and consumption were valued at USD 72 billion, and this value is expected to increase to USD 98 billion per year by 2026 (INBAR 2021). Almost 900 species, approximately 60% of bamboo species globally, are found in Asia (Liu *et al*. 2018a; Xu *et al*. 2020). There are 70 bamboo species spread across Malaysia in the Peninsular (50 species), Sabah (30 species), and Sarawak regions (20 species) (Wong 1989).

Bamboo plants are utilized for food, handicraft, construction, and industrial purposes (Chaowana and Barbu 2017). Various bamboo products are exported, including articles of daily use, kitchenware and tableware, construction materials, furniture, woven bamboo products, shoots, bamboo charcoal, and many more. The three largest product exports are bamboo articles of daily use (USD 798 million), bamboo tableware and kitchenware (USD 680 million), and bamboo shoots (USD 295 million) (INBAR 2019).

In Malaysia, industrial-grade charcoal is manufactured typically from mangrove woods (commonly *Rhizophora apiculata* and *Rhizophora mucronata*). With the increasing concerns about the availability of mangroves and the environmental sensitivity of mangrove forests, there is renewed interest in using a renewable, plantation-grown, abundantly available biomass such as bamboo as the raw material for charcoal production. Bamboo charcoal is produced through a process called carbonization or complete pyrolysis, which breaks down complex carbonaceous substances into elemental carbon and chemical compounds by heating in the absence of oxygen (Burnette 2013).

Bamboo charcoal has been used to substitute wood and mineral coal (Jiang 2007). Bamboo is a fast-growing plant; thus, it takes 3 to 4 years for bamboo culms to reach their maximum height and weight suitable for the commercial production of charcoal (Guan 2004; Jiang 2004). Compared with wood charcoal, several characteristics of bamboo charcoal make it superior. Bamboo charcoal has an enormous surface area to mass ratio and unique microporous structure, contributing to its high adsorption capacity (Huang *et al*. 2014; Isa *et al*. 2017; Kaur *et al*. 2018). Bamboo charcoal has a very high specific surface area of 150 to 400 m^2/g, approximately two or three times larger and has about four times more cavities, three times more mineral content, and four times higher adsorption capacity than wood charcoal (Kaur *et al*. 2018). Huang *et al*. (2014) stated that the large surface area and porosity of bamboo charcoal could reduce carbon dioxide emissions. Due to its ability to adsorb a wide range of materials, including chemicals, minerals, radiowaves, odours, harmful substances, and humidity, it has been utilized in household items (air freshener, fruits and vegetable saver, humidity and odour adsorbent, and water filtration) (Isa *et al*. 2017).

Another advantage of using bamboo charcoal is that the production and usage of bamboo charcoal are more environmentally friendly than wood. According to Partey *et al*. (2017), the total eco-cost (inclusive of eco-cost of human health, ecosystems, resource depletion, and global warming) from the production of charcoal from *Bambusa balcooa* was lower than the production of charcoal from wood species such as *Tectona grandis* and *Acacia auriculiformis*. Bamboo has a high density, drought resistance, and somewhat higher heating value when compared to other biomass materials (Truong and Le 2014). It is also suitable for the environment where bamboo charcoal burns clean and smokeless as it has less volatile matter.

Most bamboo charcoal production in India uses metal oil drums as its carbonizing kiln (Biswas 2000). In Thailand, people in rural areas still produce charcoal using the traditional way of using earth kilns (Sangsuk *et al*. 2018). Although it is easy to build and low-cost, the charcoal obtained from earth kilns was of low quality with high tar content and volatile matter (Sangsuk *et al*. 2018). There are several methods of producing bamboo charcoal which include using earthen kiln (Hwang 2016), tubular furnace (Liu *et al*. 2018b), electric furnace (Negara *et al*. 2017), muffle furnace (Sahoo *et al*. 2021), oil barrel kiln (Yordsri *et al*. 2018), metal kiln (Sangsuk *et al*. 2018), and steel drum kiln (Iwasaki 2015).

Iwasaki kiln is a steel drum kiln design created by Masato Iwasaki from Ashikaga Institute of Technology College, Tochigi Prefecture, Japan. The concept used in the Iwasaki kiln is the indirect burning or steaming of raw material without oxygen (Iwasaki 2015). The raw material comes in direct contact with the hot gases and becomes carbonized (Emrich 1985). This design was first created specifically to produce bamboo or wood charcoal, which can be used to reduce soil acidity. Using the Iwasaki kiln can take a shorter time to make charcoal as a high temperature of about 750 to 1000 °C is used. Wood (diameter less than 5 cm) charcoal takes less than five hours to make, while bamboo charcoal only takes three hours (Iwasaki 2015). The Iwasaki kiln can also make charcoal from corn cobs, sunflower stems, wheat husks, coffee husks, coconut husks, plants, or flower petals. A few other charcoal types successfully produced using the Iwasaki kiln have been *Leucaena leucocephala* wood charcoal (Pimsuta *et al*. 2018) and *Muntingia calabura* wood charcoal (Wittayakun *et al*. 2020). The design of the Iwasaki kiln is constructed by using two steel drums. It consists of two sections: the carbonization furnace and the firewood chamber. One steel drum is cut in half (circular cross-section) to make the firewood chamber, while another steel drum is used to make the carbonization furnace of the kiln. The firewood chamber and carbonization furnace are welded together to become a kiln. A chimney pipe is built and attached to the carbonization furnace, and this is where hot air will be released from the kiln. Bamboo vinegar (by-product) can also be collected here.

The objectives of this study were to produce bamboo charcoal from five selected species of bamboo from Sarawak, Malaysia, namely, *Dendrocalamus asper* (buluh betong), *Bambusa vulgaris* (buluh minyak), *Gigantochloa hasskarliana* (buluh busi), *Gigantochloa levis* (buluh beting), and *Schizostachyum brachycladum* (buluh lemang) using a modified version of Iwasaki's high-speed charcoal kiln design. This study was also conducted to determine and compare the quality of bamboo charcoal produced based on proximate analysis. The information obtained from this study will evaluate the suitability of these bamboo species for charcoal production.

EXPERIMENTAL

Kiln Preparation

A steel drum kiln was constructed for this project. The design was based on Iwasaki's high-speed charcoal kiln design, with a few modifications. The modifications included an opening on the top of the firewood chamber, and the chimney was set up as an exhaust vent, not to distil vinegar and tar. This design was chosen because it is simple, easy to construct, cost-effective, and can be mobilized conveniently.

Two tight-head steel drums with a capacity of 208 L (914 mm in height and 600 mm in diameter) were used to make the drum kiln. One steel drum was laid horizontally on its side for the carbonization chamber. Two 60 cm width x 50 cm length openings were cut at about 10 cm from both sides of the drum. A hole of about nine cm in diameter was drilled at the bottom of the drum, and then a funnel was attached to it vertically. At the bottom of the drum, an opening of 35 cm length x 9 cm width was cut for a hot air passage to flow from the firewood chamber to the carbonization chamber.

The other steel drum was cut in half to build the firewood chamber. At the top of one half of the drum, an opening of 18 cm width x 20 cm length was cut. At the side of the drum, an opening of 60 cm width x 50 cm length was cut. During the carbonization, firewood was loaded and reloaded through this opening. The remaining half of the second steel drum was used to cover the openings in the carbonization and firewood chambers. The two drums were attached and welded together. A chimney was then attached to the hole made at the carbonization chamber. The hot air generated from the carbonization process was released through this chimney. The bamboo vinegar was not collected.

With a space of about 2.5 m x 1.5 m, a rectangular wall enclosure was constructed about 20 cm from the kiln. As the kiln was laid horizontally, soil and brick were filled and arranged to support the kiln. Soil was filled up until about 10 cm from the carbonization openings to act as an insulator.

Sample Preparation

Bamboo samples of four years old, namely *Gigantochloa hasskarliana*, *Gigantochloa levis*, and *Schizostachyum brachycladum*, were collected from Kampung Barieng, Bau, in Sarawak, Malaysia. *Bambusa vulgaris* was collected in Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Sarawak, Malaysia while *Dendrocalamus asper* was collected in Kampung Lintang, Sri Aman, Sarawak, Malaysia. These bamboos were found on farmland owned by villagers.

During the sample collection, several factors were considered, such as the age of the bamboo culm, ease of felling bamboo culm, and safety level. Mature culms of approximately four years were selected. The appearance of a small circle or speck of white-colored lichen characterized the mature bamboo culm. These lichens partially cover the trunk, which still maintains its green color. Old or over-mature bamboo is usually covered with excessive fungi and mosses and turns brown in color. Determination of bamboo age in the field was assisted mainly by the locals or owners of the farmland.

Two culms from each selected species were chosen. The culms were cut at about 15 cm above ground level. The total length of each felled culm was measured, and the internode number was marked starting from no. 1 at the bottom until internode no. 30 at the top. The bamboo culm at the designated internodes was measured for its length, diameter, and culm wall thickness. The basic density of the bamboo specimen was determined based on oven-dry weight and green volume basis.

The culms were divided into three sections for bamboo charcoal production according to the position of internodes from the ground. The bottom section is the first two meters of the felled bamboo culm, and the middle section is the culm's midsection (the next two meters). The top section is the section above the midsection of the felled culm. The bamboo samples from each section were cut at internodes to a shorter length of 80 cm to fit the kiln. Each cut was split in half before airdrying. Airdrying was conducted to remove excess water content in the bamboo splits to avoid exploding during the kiln's carbonization process. Subsequently, the airdried samples were weighed and recorded before carbonization.

Carbonization

The bamboo splits were stacked in the kiln and arranged alternately. The splits were positioned 5 cm from each other to prevent overcrowding. At least a 5 cm gap was left at the top for hot air to pass through. Depending on the size of the bamboo splits, the maximum number of splits was 55 to 56 splits in each carbonization batch. The opening of the carbonization furnace was closed, and spaces along the edge of the lid were sealed with sticky clay to prevent air from entering the drum kiln during carbonization. The kiln was covered with more soil (until approximately 10 cm thick) as an insulator. The soil was packed carefully and thoroughly so that air could not enter.

Firewood was inserted into the firewood chamber. Soon after the fire was ignited, the kiln temperature was monitored regularly using an infrared thermometer and a K-type thermometer. For this project, the carbonization temperature chosen was 750 ± 50 °C. Firewood was constantly fed into the firewood chamber to ensure the temperature increased steadily until the targeted temperature was achieved. After 2 h, the carbonization temperature of 750 ± 50 °C was achieved. The carbonization temperature was maintained for another two hours before the entrance of the firewood chamber was closed and blocked with bricks and soil to maintain the state of no oxygen. Then, the kiln was left to cool down overnight. The charcoal was collected the next day after the kiln had cooled completely.

Determination of Bamboo Charcoal Yield Percentage

Bamboo charcoal from all five species was collected the next day and weighed. The bamboo charcoal yield percentage was calculated according to Eq. 1,

$$\text{Yield (\%)} = \left(\frac{W_1 - W_2}{W_1}\right) \times 100\% \qquad (1)$$

where W_1 is the oven-dry weight of the bamboo sample and W_2 is the oven-dry weight of charcoal.

Proximate Analysis

Proximate analysis was conducted on the charcoal produced to determine the fixed carbon, volatiles, ash, and moisture content. Proximate analysis in this project was carried out according to the ASTM D1762-84 (2013). Moisture content (MC) (%) was calculated using Eq. 2,

$$\text{Moisture content \%} = \left(\frac{A-B}{A}\right) X\ 100\% \qquad (2)$$

where A and B represent the weight (g) of airdried sample used and the weight (g) of sample after oven-drying at 105°C, respectively.

Volatile matter content (VMC) (%) was calculated based on the following formula,

$$\text{Volatile matter content \%} = \left(\frac{B-C}{B}\right) \text{X}\ 100\% \qquad (3)$$

where B and C represent the weight (g) of the sample after oven-drying at 105 °C and the weight (g) of the sample after drying at 950 °C, respectively.

Ash content (AC) (%) was calculated as follows,

$$\text{Ash content \%} = \left(\frac{D}{B}\right) X\ 100\% \qquad (4)$$

where B and D represent the weight (g) of sample after oven-drying at 105 °C and weight (g) of the residue, respectively.

Fixed carbon (FC) content (%) was obtained using the following formula.

$$\text{FC (\%)} = 1 - \text{MC} - \text{VMC} - \text{AC} \qquad (5)$$

Gross Caloric Value

The gross calorific value (GCV) was determined using proximate analyses values based on Majumder *et al*. (2008), based on Eq. 6,

$$\text{GCV} = -\ 0.03(\text{AC}) - 0.11(\text{M}) + 0.33(\text{VM}) + 0.35(\text{FC}) \qquad (6)$$

where GCV unit is megajoule per kilogram (MJ/kg), and AC, M, VM, and FC represent ash content, moisture content, volatile matter and fixed carbon, respectively.

Data Analysis

The data obtained were analyzed using a Two-Way Analysis of Variance (ANOVA). The factors involved were the three sections of bamboo culm (bottom, middle, top) and the five different species. Tukey's HSD test was used as a post-hoc test to compare means differences among bamboo species and the culm section. An alpha level of significance of 0.05 was used for all tests.

RESULTS AND DISCUSSION

Bamboo Morphological Features

The mean total bamboo height recorded ranged from 11.4 to 21.7 m, with *B. vulgaris* measured as the highest (Table 1). The size of a mature bamboo is governed by the species, and it varies according to clump density and age (Liu *et al*. 2016). Topographic features, soil conditions (Skovsgaard and Vanclay 2008), temperature, relative humidity, and elevation (Aribal *et al*. 2022) may cause differences in bamboo height growth.

Table 1. Mean Morphological Features of Bamboo

Species	Culm section	Basic density (kg/m^3)	Internode length (cm)	Internode diameter (cm)	Culm wall thickness (mm)	Total culm height (m)
Dendrocalamus asper	Bottom	600^{a*}	41.7^a	13.2^b	19.8^c	13.6^{a**}
	Middle	630^b	57.0_b	11.5^b	10.3^b	
	Top	743^c	46.5^a	9.2^a	7.1^a	
Bambusa vulgaris	Bottom	562^a	29.0^a	7.4^b	13.3^c	21.7^c
	Middle	655^b	38.0^b	6.5^b	7.1^b	
	Top	700^c	32.0^a	4.2^a	6.2^a	
Gigantochloa hasskarliana	Bottom	390^a	35.5^a	4.7^b	6.1^b	
	Middle	482^b	48.5^c	4.3^a	3.6^a	$19.9b^c$
	Top	555^c	28.0^a	4.1^a	3.5^a	
Gigantochloa levis	Bottom	477^a	58.5^b	4.2^b	9.6^c	11.4^a
	Middle	506^b	53.5^b	$.3.7^a$	5.9^b	
	Top	577^c	41.5^a	3.0^a	4.4^a	
Schizostachyum brachycladum	Bottom	589^a	85.0^b	5.4^b	5.2^c	17.7^b
	Middle	692^b	89.0^b	5.2^a	3.2^b	
	Top	757^c	51.0^a	5.1^a	2.6^a	

*Mean values of the culm section within a species followed by different numbers indicate significant differences at $P < 0.05$ using Tukey's test.
**Mean values in the same column followed by different letters indicate significant differences at $P < 0.05$ using Tukey's test.

Bamboo's basic density (oven-dry weight green volume basis) increased with height. According to Itoh (1990), the basic density varies due to the maturation process, starting from the bottom section of the bamboo to the top section. The findings are consistent with other studies which also reported an increment in the basic density of the culm with increasing height levels of the bamboo culm (Nordahlia *et al*. 2012; Falayi and Soyoye 2014; Santhoshkumar and Bhat 2014; Gebremariam and Assefa 2018). This is because there are more parenchyma cells (Yu 2008) and lesser compact vascular bundles (Zakikhani *et al*. 2017) in the bottom section than in the top section of the culm.

The internode length of *D. asper, B. vulgaris,* and *G. hasskarliana* showed that the length increases from the bottom to the middle section, then gradually decreases towards the top section. However, the internode length of *G. levis* and *S. brachycladum* showed the opposite trend. Darwis and Iswanto (2018) reported that the internode length in the middle section of *B. vulgaris* is longer than that of the bottom and top sections. Similarly, the shortest internode length of *G. atter* is from the bottom section of the bamboo culm (Marsoem *et al*. 2015). Razak *et al*. (2007) also reported that the length of internodes for *G. scortechinii* increases from the bottom to the middle section of the culm and decreases towards the top section.

Generally, the internodes diameter and culm wall thickness of all bamboo species decrease from the bottom towards the top section of the bamboo culm. Zakikhani *et al*. (2017) found that the diameter of *D. pendulus*, *D. asper*, *G. levis*, and *G. scortechinii* decreases from the bottom section to the top of the bamboo culm. Darwis and Iswanto (2018) stated that the inner diameter of the internodes at the middle section of *B. vulgaris* culm is larger than the inner diameter at the bottom and the top sections.

Bamboo Charcoal Yield

Dendrocalamus asper and *B. vulgaris* produced a significantly lower yield of bamboo charcoal than the other three species, namely *G. hasskarliana*, *G. levis*, and *S. brachycladum* (Table 2). The highest overall mean dry yield was recorded for *G. levis* at 55.2%, followed by *G. hasskarliana* (53.7%) and *S. brachycladum* (50.2%). The lowest overall mean yield was recorded for *B. vulgaris* at 8.8%. The mean weight of charcoal obtained from each carbonization run for *D. asper*, *B. vulgaris*, *G. hasskarliana*, *G. levis*, and *S. brachycladum* was 5482 g, 1975 g, 1432 g, 246 g, and 397 g, respectively. No significant differences between the yield of bamboo charcoal produced from different sections (bottom, middle and top) were observed.

A more than 30% yield is considered a good and efficient performance (Panyathanya *et al*. 1998). Charcoal yield from carbonization processes using earth-mount kilns, metallic kilns, and industrial processes rarely reaches 30% (Antal and Gronli 2003). All five species from this study showed a good dry weight yield of more than 30%, except for *B. vulgaris* and *D. asper*. This may be due to the culm thickness of both species, rendering it difficult to be converted into charcoal, especially at the bamboo culm's outer wall. However, the yield percentage of charcoal from *G. hasskarliana*, *G. levis*, and *S. brachycladum* showed a high yield indicating great success in converting bamboo culm to bamboo charcoal for these species.

Table 2. Mean Dry Yield (%) of Bamboo Charcoal

Species	Bottom (%)	Middle (%)	Top (%)	Overall Mean (%)***
Dendrocalamus asper	26.6^{b*2**}	22.2^{b1}	9.2^{a1}	19.3^{1}
Bambusa vulgaris	10.0^{b1}	9.8^{b2}	6.6^{a1}	8.8^{1}
Gigantochloa hasskarliana	53.5^{ab3}	44.0^{a3}	63.5^{b3}	53.7^{2}
Gigantochloa levis	67.4^{b4}	57.6^{b4}	40.7^{a2}	55.2^{2}
Schizostachyum brachycladum	50.0^{a3}	51.8^{a5}	48.8^{a2}	50.2^{2}

*Mean values in the same row followed by different letters indicate significant differences at $P < 0.05$ using Tukey's test.
**Mean values in the column followed by different numbers indicate significant differences at $P < 0.05$ using Tukey's test.
*** Overall mean is the mean yield for the combined bottom, middle, and top sections.

Proximate Analysis

Moisture content

Table 3 presents the moisture content percentage obtained through the proximate analysis of the bamboo charcoal samples. The lowest mean moisture content recorded was for *D. asper* (5.1%), followed closely by *G. hasskarliana* at 5.3%. The overall mean moisture content percentage in bamboo charcoal from *G. levis* was significantly higher than those of the other species. Significant differences in the mean moisture content percentage values among different bamboo sections (bottom, middle, and top) were recorded for all species except *S. brachycladum*. In *D. asper* and *G. levis* the highest mean moisture was in the bottom and middle sections. For *B. vulgaris,* the highest mean moisture content was in the bottom section. Moisture content variation among sections is caused by the distribution of parenchyma cells and vascular bundles within the culm. The moisture content of the top section is the lowest due to the density of parenchyma cells decreasing as the culm height increases and vascular bundles becoming more compact (Zakikhani *et al*. 2017). The culm wall is thickest at the bottom, with more parenchyma cells, resulting in higher water-holding capacity at the bottom than in the top section (Qisheng *et al*. 2002; Yu 2008).

Table 3. Mean Moisture Content of Bamboo Charcoal

Species	Bottom (%)	Middle (%)	Top (%)	Overall Mean (%)***
Dendrocalamus asper	5.3^{b*1**}	5.5^{b1}	4.5^{a1}	5.1^{1}
Bambusa vulgaris	6.2^{b2}	5.4^{a1}	5.3^{a2}	5.6^{4}
Gigantochloa hasskarliana	5.2^{a1}	5.5^{b1}	5.1^{a12}	5.3^{1}
Gigantochloa levis	7.5^{b3}	8.1^{b2}	6.6^{a3}	7.4^{3}
Schizostachyum brachycladum	6.0^{a2}	6.1^{a3}	6.3^{a3}	6.1^{2}

*Mean values in the same row followed by different letters indicate significant differences at P < 0.05 using Tukey's test.
**Mean values in the column followed by different numbers indicate significant differences at P < 0.05 using Tukey's test.
***Overall mean is the mean moisture content for the combined bottom, middle, and top sections.

The highest mean moisture content in *G. hasskarliana* was recorded in the middle section. The quality specifications for charcoal usually require the charcoal's moisture content to range between 5% and 15%, as charcoal with more than 10% moisture content percentage was found to be brittle and produced fines when heated in blast furnaces (FAO 1987). Therefore, charcoal with lower moisture content was classified as more economically valuable because it eased the handling and transportation process. Charcoal with high moisture content could cause problems when used directly, as the moisture will reduce the calorific value of the charcoal, and when the charcoal contains high moisture content, more charcoal is needed during burning (Rahman *et al*. 2019) and requires more energy for drying prior to carbonization (Ajimotokan *et al*. 2019). Park *et al*. (2019) reported the moisture content of *D. asper* and *B. vulgaris* charcoal at 7.1% and 10.2%, respectively, which was considered high. They reported that the high moisture content was highly affected by the thickness of the culm.

The moisture content of bamboo charcoal from all five bamboo species was less than 8%, in conformity with the provisions of international markets. Charcoal which contains a moisture content of greater than 8% induced greater material consumption during combustion mainly because the excess water needs to be evaporated (Heya *et al*. 2014). Charcoal with lower moisture contents is preferred as they are more resistant to biodegradation, environmentally stable, and less susceptible to biological agents.

Volatile matter content

The lowest mean volatile matter content recorded was for *G. hasskarliana* (22.8%), followed closely by *D. asper* at 24.0% (Table 4). The overall mean volatile matter content percentage in bamboo charcoal from *B. vulgaris* and *S. brachycladum* was significantly higher than all other species, recorded at 34.5% and 32.1%, respectively. There were no significant differences in the mean values of volatile matter content percentage among different sections of bamboo (bottom, middle, top) for all species except for *B. vulgaris* and *S. brachycladum*. For *B.vulgaris* and *S. brachycladum,* the highest mean volatile matter content was recorded in the top section.

Table 4. Mean Volatile Matter Content Percentage of Bamboo Charcoal

Species	Bottom (%)	Middle (%)	Top (%)	Overall Mean (%)***
Dendrocalamus asper	21.2^{a*1**}	26.6^{a12}	24.1^{a2}	24.0^{13}
Bambusa vulgaris	32.7^{a2}	32.0^{a23}	38.7^{b3}	34.5^{2}
Gigantochloa hasskarliana	25.9^{a1}	22.1^{a1}	20.4^{a1}	22.8^{1}
Gigantochloa levis	24.1^{a1}	26.3^{a12}	27.6^{a2}	26.0^{3}
Schizostachyum brachycladum	23.8^{a1}	34.7^{b3}	37.7^{b3}	32.1^{2}

*Mean values in the same row followed by different letters indicate significant differences at $P < 0.05$ using Tukey's test.
**Mean values in the column followed by different numbers indicate significant differences at $P < 0.05$ using Tukey's test.
***Overall mean is the mean volatile matter content for the combined bottom, middle, and top sections.

Charcoal with low volatile matter content works better as fuel (Heya *et al*. 2014). Park *et al*. (2019) stated that volatile matter content in charcoal produces soot and smoke when present in a high percentage, which is an unwanted factor during combustion. Charcoal with high volatile matter content could be helpful during the ignition process and speed up the combustion, but it would also produce unwanted tars and emit fumes (Bustamante-Garcia *et al*. 2014).

Volatile matter in charcoal could vary from as low as 5% to as high as 40% (FAO 1987), while Antal and Gronli (2003) and Williamson (2006) stated that the volatile matter content of high-quality charcoal ranged between 20 and 30% for domestic usage. In this study, the volatile matter content of *G. hasskarliana*, *G. levis*, and *D. asper* met the desirable criteria.

Ash content

The lowest overall mean ash content recorded was for *D. asper* (3.9%), followed closely by *B. vulgaris* and *G. hasskarliana* at 5.3% and 5.6%, respectively (Table 5). The overall mean ash content percentage in bamboo charcoal from *G. levis* (17.1%) and *S. brachycladum* (15.3%) was significantly higher than all other species recorded. Significant differences were found in the mean values of ash content percentage among different sections of bamboo (bottom, middle, top) for all species except for *G. hasskarliana* and *G. levis*. The highest mean ash content recorded for *D. asper*, *G. hasskarliana* and *S.*

brachycladum was in the top section. The highest mean ash content recorded in charcoal made from *B. vulgaris* was in the bottom section. High ash content in bamboo is attributed to high silica content (Kumar and Chandrashekar 2014).

Table 5. Mean Ash Content of Bamboo Charcoal

Species	Bottom (%)	Middle (%)	Top (%)	Overall Mean (%)***
Dendrocalamus asper	2.9^{a1}	3.1^{a1}	5.6^{b1}	3.9^{1}
Bambusa vulgaris	7.7^{b23}	4.4^{a1}	3.8^{a1}	5.3^{1}
Gigantochloa hasskarliana	4.6^{a12}	4.5^{a1}	7.8^{b1}	5.6^{1}
Gigantochloa levis	14.9^{a4}	16.9^{a2}	19.4^{a2}	17.1^{2}
Schizostachyum brachycladum	9.1^{a3}	16.1^{b2}	20.8^{c2}	15.3^{2}

*Mean values in the same row followed by different letters indicate significant differences at P < 0.05 using Tukey's test.
**Mean values in the column followed by different numbers indicate significant differences at P < 0.05 using Tukey's test.
*** Overall mean is the mean ash content for the combined bottom, middle, and top sections.

The ash content percentage is important for selecting a biomass fuel (Ruiz-Aquino 2019). Generally, a high ash content biomass is not preferred, as it reduces the charcoal's calorific value and combustion quality (Park *et al*. 2019). High ash content could cause accumulating ashes, which disturb the flow of combustion gases inside biomass boilers (Werkelin *et al*. 2011). High ash-content charcoal could also cause corrosion, erosion, and abrasion (Ruiz-Aquino 2019).

According to Antal and Gronli (2003), the ash content of high-quality charcoal could vary from 0.5% to 5% or slightly more than 5%, depending on the wood species used. Among the five species in this study, three species achieved the desired qualification based on the ash content, namely *D. asper*, *G. hasskarliana*, and *B. vulgaris,* with ash content slightly above 5% (ranging between 3.9% and 5.6%).

Park *et al*. (2019) reported a lower ash content percentage in bamboo charcoal from *B. vulgaris* (carbonized at 600 to 800 ºC). However, the difference may be attributed to the different methods of carbonization used in the current study and the study done by Park *et al*. (2019), which used a laboratory electric furnace instead of a kiln. In mangrove charcoal, the ash content percentage reported was similar to our current study, at 4.5% (Nurhayati 1990) and 6.3% (Rahman *et al*. 2019), respectively.

Fixed carbon content

The mean fixed carbon content percentage obtained through the proximate analysis of the bamboo charcoal samples is presented in Table 6. The lowest mean fixed carbon content recorded was for *S. brachycladum* (46.5%), followed closely by *G. levis* at 49.5%. The overall mean fixed carbon content percentage in bamboo charcoal from *D. asper* and *G. hasskarliana* were significantly higher than all other species, recorded at 67.1% and 66.3%, respectively. Among bamboo sections (bottom, middle, top), there were no significant differences in the fixed carbon content for all species except in *B. vulgaris* and *S. brachycladum*. For *B. vulgaris,* the highest mean fixed carbon content recorded was in the middle section. The highest mean fixed carbon content for *S. brachycladum* was recorded in the bottom section.

The fixed carbon content of charcoal could vary among species, ranging from approximately 50% to as high as 95% (FAO 1987). Demirbas (2001) indicated that low carbon content enhanced friability and fragility while lowering the resistance to compression and cohesion. Heya *et al*. (2014) stated that the European market's requirement for fixed carbon content for industrial purposes exceeds 75%. In this study, except for *G. levis* and *S. brachycladum*, the three other species, namely *B. vulgaris*, *D. asper*, and *G. hasskarliana*, recorded fixed carbon content of above 50%. Previous studies recommended that the maximum temperature and residence time during the carbonization process can control the fixed carbon content (Hindi 1994; Dionco-Adetayo 2001). The charcoal produced at a higher temperature had higher fixed carbon content than the charcoal produced at a lower temperature (Dionco-Adetayo 2001). The fixed carbon content reported in this study was slightly lower than that of *R. apiculata* and *R. mucronata* charcoal, which was 73% and 72%, respectively (Yatim 1987).

Table 6. Mean Fixed Carbon Content Percentage of Bamboo Charcoal

Species	Bottom (%)	Middle (%)	Top (%)	Overall Mean (%)***
Dendrocalamus asper	70.6^{a3}	64.9^{a23}	65.8^{a3}	67.1^{1}
Bambusa vulgaris	53.3^{a1}	58.1^{b2}	52.2^{a2}	54.6^{4}
Gigantochloa hasskarliana	64.3^{a23}	67.8^{a3}	66.8^{a3}	66.3^{1}
Gigantochloa levis	53.5^{a1}	48.7^{a1}	46.4^{a2}	49.5^{2}
Schizostachyum brachycladum	61.1^{c2}	43.1^{b1}	35.3^{a1}	46.5^{23}

*Mean values in the same row followed by different letters indicate significant differences at P < 0.05 using Tukey's test.
**Mean values in the column followed by different numbers indicate significant differences at P < 0.05 using Tukey's test.
***Overall mean is the mean fixed carbon content for the combined bottom, middle, and top sections.

Park *et al*. (2019) reported higher values of fixed carbon content in *B. vulgaris* and *D. asper* charcoal (carbonized at 600 to 800 °C) at 77.5 to 85.3% and 72.7 to 75.0%, respectively. The fixed carbon content is related to the volatile matter content of charcoal, and the charcoal with lower volatile matter content will have higher fixed carbon content and *vice versa*. Charcoal with low volatile matter content and high fixed carbon content is generally heavier, stronger, and more burning and heating but is more difficult to ignite (Sayakoummane and Ussawarujikulchai 2009).

Gross Caloric Value

The energy potential of the bamboo charcoal was estimated based on gross calorific value (GCV) or high heating value. Calorific value is the amount of heat released during the combustion of fuel, and it is an important attribute in evaluating the quality of solid biofuels (Antwi-Boasiako and Glalah 2021). The overall mean GCV was found to be between 24.4 and 29.2 MJ/kg (Table 7). This result is similar to the findings of a few studies. Kumar and Chandrashekar (2014) observed the GCV of four bamboo species was between 25.1 and 28.7 MJ/kg carbonized at 700 and 800 ^{0}C. The calorific value of *Dendrocalamus giganteus* (Sembilang bamboo) and *Phyllostachys edulis* (Moso bamboo) reported by Park *et al*. (2020) carbonized at 800 ^{o}C was 28.3 and 31.9 MJ/kg, respectively.

The mean calorific values *of D. asper*, *B. vulgaris,* and *G. hasskarliana* were higher than those of *G. levis* and *S. brachycladum*.

Generally, the GCV was similar among the culm sections of all bamboo species. The heating values of 28.0 and 32.0 MJ/kg were reported for planted trees of *Gmelina arborea* and *Paraserianthes falcataria*, respectively (Hidayat *et al*. 2017). The GCV of wood charcoal of five tree species ranged from 29.3 to 32.2 MJ/kg (Ruiz-Aquino *et al.* 2019). The energy potential of the bamboo species studied is close to that of wood charcoal. Since the growing and harvestable rate of bamboo is much faster than timber, thus bamboo has a good prospect for solid biofuel (Truong and Anh Le 2014).

Table 7. Gross Calorific Value of Bamboo Charcoal

Species	Bottom	Middle	Top	Overall mean
Dendrocalamus asper	29.3^{a2}	29.1^{a2}	29.0^{a2}	29.1^{2}
Bambusa vulgaris	28.5^{a1}	28.5^{a2}	28.9^{a2}	28.6^{2}
Gigantochloa hasskarliana	29.2^{a2}	29.1^{a2}	29.2^{a2}	29.2^{2}
Gigantochloa levis	25.3^{a1}	24.2^{b1}	23.9^{a1}	24.4^{1}
Schizostachyum brachycladum	28.2^{b1}	25.3^{a1}	23.3^{a1}	25.6^{1}

*Mean values in the same row followed by different letters indicate significant differences at P < 0.05 using Tukey's test.
**Mean values in the column followed by different numbers indicate significant differences at P < 0.05 using Tukey's test.
*** Overall mean is the mean yield for the combined bottom, middle, and top sections.

CONCLUSIONS

1. The length of the internodes increased from the bottom section to the middle section of the culm, then gradually decreased towards the top section for *D. asper, B. vulgaris* and *G. hasskarliana*. The internodes diameter and culm wall thickness decreased, while basic density increased with height.
2. The carbonization at 750 ºC using a modified Iwasaki steel drum kiln successfully produced bamboo charcoal from *B. vulgaris, D. asper*, *G. hasskarliana*, *G. levis,* and *S. brachycladum* of acceptable quality, suggesting the suitability for the bamboo to be made into charcoal, especially for domestic use
3. The bottom section of all bamboo species produced a superior quality of charcoal compared to the upper sections due to its lower moisture, volatile, ash, and high fixed carbon content.
4. *Gigantochloa hasskarliana* produced the highest quality bamboo charcoal in terms of low moisture content, volatile matter content, ash content, and highest fixed carbon content and gross calorific value of all bamboo charcoal evaluated.
5. The yield of bamboo charcoal obtained from *G. hasskarliana* was the highest, followed by *D. asper*.

ACKNOWLEDGMENTS

The authors thank the Institute of Creative Arts and Technology (iCreaTe), the Faculty of Resource Science and Technology, Universiti Malaysia Sarawak, and Sarawak Timber Industry Development Corporation for their support and support assistance. The authors are grateful to Kursi Pusaka grant (GL/I04/SCBS/2019) and Danish Technological Institute (GL/FO7/DTI/2019) for funding this research.

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Article submitted: April 3, 2023; Peer review completed: April 20, 2023; Revised version received and accepted: April 29, 2023; Published: May 3, 2023.
DOI: 10.15376/biores.18.3.4413-4429