Anatomical Characteristics for Identification and Quality Indices of Four Promising Commercial Bamboo Species in Java, Indonesia

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The anatomical characteristics in the culms of the four promising Indonesian bamboo species, including *Dendrocalamus asper*, *Dendrocalamus giganteus*, *Bambusa vulgaris* var. *vulgaris*, and *Bambusa vulgaris* var. *striata,* were investigated to produce an identification key and quality indices for further effective utilization. The crystalline properties of the bamboo culm were determined using X-ray diffraction analysis. *Dendrocalamus asper* and *Bambusa vulgaris* var. *striata* showed vascular bundle type IV, while *Dendrocalamus giganteus* and *Bambusa vulgaris* var. *vulgaris* displayed vascular bundle type III. The vascular bundle density in the bamboo culms increased from the bottom to the top part and was higher in the outer part than in the inner part. The fiber portion and length in the outer part were higher than those in the inner part, opposite of those in the parenchyma portion. *Dendrocalamus giganteus* had the largest vessel and parenchyma diameter, while *Bambusa vulgaris* var. *vulgaris* had the smallest. *Bambusa vulgaris* var. *vulgaris* had the longest parenchyma, while *Bambusa vulgaris* var. *striata* and *Dendrocalamus giganteus* had the shortest. The outer part of the four bamboo culms showed higher relative crystallinity than the inner part. All anatomical parameters, except for crystallite width, showed a variation in the radial direction of the four bamboo culms but did not show a consistent tendency vertically. This study revealed that the anatomical properties were different between bamboo species and could be used for species identification and quality evaluation indices of the culms.

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INTRODUCTION

Bamboo is a multipurpose plant that provides many benefits. Ecologically, bamboo stands have a role in erosion control and riverbank protection (Osei *et al.* 2019). Bamboo is also used as a food and building material to provide social and economic value (Satya *et al.* 2010; Manandhar *et al.* 2019). Recently, interest in bamboo utilization has increased alongside the demand for alternative wood and lignocellulosic raw materials. Several studies have reported the use of bamboo culm in various products, such as bioenergy (Park *et al.* 2018, 2019), composite materials (Febrianto *et al.* 2012, 2015; Maulana *et al.* 2021a), and nanocellulose materials (Jang *et al.* 2020; Rasheed *et al.* 2020).

The diversity of bamboo species provides a challenge in determining the appropriate use of bamboo species. A total of 1642 bamboo species from 75 genera have been identified worldwide (Vorontsova *et al.* 2016). There are 161 bamboo species from 12 native genera in Indonesia, including *Dendrocalamus*, *Bambusa*, *Gigantochloa*, *Schizaostachyum*, *Nastus*, *Dinochloa*, *Fimbribambusa*, *Neololeba*, *Pinga*, *Racemobambos*, *Sphaerobambos*, and *Parabambusa* (Widjaja *et al.* 2014). The classification of species and genera of bamboo is mainly based on the morphology of its reproductive structure (Clark *et al.* 2015). This allows species in the same genus to have different anatomical characteristics and species with similar anatomical characteristics to be grouped into different genera. In addition, the physical and mechanical properties of bamboo could be influenced by its anatomical characteristics; therefore, studying the anatomical characteristics of bamboo culms is essential.

Anatomically, the bamboo culm tissue is mostly parenchyma and the vascular bundles. The vascular bundles are composed of vessels, sieve tubes with companion cells, and fibers. The cell compositions of the bamboo culm are about 50% parenchyma, 40% fiber, and 10% conducting tissues (vessels and sieve tubes) with some variation according to species (Liese 1987). Moreover, the anatomical characteristics of bamboo also vary within culms, such as in the radial and axial directions.

There are several studies on the variation of anatomical characteristics within the bamboo culm. Huang *et al.* (2015) mentioned that the larger vascular bundles and parenchyma lumen diameter are located in the middle zone of *Bambusa rigida*, and the longer fiber and parenchyma are also found in the middle zone. The vascular bundle size, vessel lumen diameter, fiber lumen diameter, parenchyma length, and lumen decrease with increasing height. Sharma *et al.* (2017) reported that the vascular bundle of *Schizostachyum manii*, *Schizostachyum munroi*, and *Schizostachyum pergracile* are larger in the middle zone of the bamboo culm. In addition, the authors revealed that the vascular bundle density increases across the bamboo culm, while the fiber dimension and the wall thickness decrease. Jeon *et al.* (2018a) mentioned that vascular bundle density, fiber length, and the relative crystallinity in the three species of *Phyllostachys* bamboo are higher at the outer part than the inner part of the culm. Darwis *et al.* (2020) reported that the fiber length of *Gigantochloa pruriens* is the greatest in the middle part and smallest in the bottom part. Maulana *et al.* (2021b) mentioned that the vascular bundle density, fiber length, and relative crystallinity of three *Gigantochloa* bamboo culms from Indonesia are higher in the outer part of the culm than the inner part.

The four bamboo species *Dendrocalamus asper, D. giganteus, Bambusa vulgaris* var. *vulgaris,* and *B. vulgaris* var. *striata* are native to Indonesia. These types have many uses and potential as alternative raw materials for the wood industry. *Dendrocalamus asper* has been used for large structure building and furniture because it has good strength and does not easily crack when drying (Minke 2011). *Dendrocalamus giganteus* has potential in structural composite materials and bio-charcoal (Sun *et al.* 2020, Park *et al.* 2020). *Bambusa vulgaris* var. *vulgaris* has been widely cultivated as the raw material for pulp and paper in Brazil (Júnior *et al.* 2019). Meanwhile, *Bambusa vulgaris* var. *striata* has long been used as a temporary building material in Balinese traditional ceremonies (Arinasa and Bagus 2010).

Although these bamboo species have been used in various applications, the anatomical characteristics of these bamboos are rarely reported. In addition, there has been no study on the radial and axial variation of anatomical characteristics in *Dendrocalamus asper*, *D. giganteus*, *Bambusa vulgaris* var. *vulgaris*, and *B. vulgaris* var. *striata*. Therefore, the anatomical characteristics of *D. asper*, *D. giganteus*, *B. vulgaris* var. *vulgaris*, and *B. vulgaris* var. *striata* culms in the radial and axial direction were investigated in order to enrich the information regarding species identification and further utilization.

EXPERIMENTAL

Materials

Three culms each from five-year-old bamboo specimens of *Dendrocalamus asper*, *Dendrocalamus giganteus*, *Bambusa vulgaris* var. *vulgaris*, and *Bambusa vulgaris* var. *striata* were collected from the bamboo garden of the Research and Development Center (P3) Biomaterials, Indonesian Institute of Sciences, Cibinong, Bogor, Indonesia (6° 29' 43.2" S, 106° 51' 11.9" E). The stems were cut at the second node above the ground, and the branched tops were removed, leaving three-quarters of the total height of the stem. These stems were divided into three parts with equal length, consisting of the top, middle, and bottom (SNI 8020: 2014 2014). Detailed information on the four bamboo materials is shown in Table 1.

Table 1. General Information of Four Bamboo Species

	D. asper			*D. giganteus*			*B. vulgaris* var. *vulgaris*			*B. vulgaris* var. *striata*		
	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom
Diameter (cm)	9.4 ±0.55	12.1 ±0.81	13.9 ±0.55	6.7 ±0.71	10.5 ±0.80	13.9 ±0.85	6.5 ±0.74	8.6 ±0.66	9.6 ±0.82	5.3 ±0.25	7.3 ±0.45	8.7 ±0.56
Culm Thickness (cm)	1.12 ±0.13	2.11 ±0.20	2.74 ±0.22	0.45 ±0.04	0.58 ±0.03	1.27 ±0.06	0.62 ±0.03	0.89 ±0.03	1.37 ±0.04	0.59 ±0.02	0.66 ±0.02	1.46 ±0.04
Height (m)	23±2.65			28±1.53			11±1.53			13±1.53		

Optical Microscopy

Bamboo blocks (10 (L) x 10 (R) x 10 (T) mm^3) were softened in a boiling mixture of glycerin and water (50:50). Thin slices with a 15 to 20 µm thickness from the cross, radial, and tangential sections were prepared with a rotary microtome (Leica RM 2165, Heidelberg, Germany). The sections were then stained with 1% safranin solution and 1% light green SF yellowish solution. Next, the stained sections were dehydrated using an ethanol series (50%, 70%, 90%, 95%, and 99%) and xylene (Jeon *et al.* 2018a). Permanent slides were made using Canadian balsam resin. For fiber length measurement, match-sized bamboo strips were macerated with a mixed solution in a 1:1 (V/V) ratio of glacial H_2O_2 and CH_3COOH at 60 °C until they were defibrillated (Franklin 1945).

In this study, the density of the vascular bundle was measured in a 4 mm^2 area. The cell proportion was determined as the ratio of the area of each cell type to the total area using optical micrographs at 4x magnification. Data on vascular bundle density and cell proportion were collected 10 and 5 times, respectively. The dimensions of fiber, vessel, and parenchyma cells were measured from 40 replications. Vascular bundle type, vascular bundle density, fiber length, parenchyma dimensions, vessel diameter, and cell proportion were observed using an optical microscope (Nikon Eclipse E600, Tokyo, Japan) and an image analyzer (IMT i-solution lite, Version 9.1, Vancouver, Canada).

X-ray Diffraction Analysis

Equatorial X-ray diffractograms of the bamboo culms were taken via reflection mode using the X-ray diffraction apparatus (Cu target, DMAX 2100V, Rigaku, Tokyo, Japan, 40 kV, 40 mA) installed at Kangwon National University, Chuncheon, Korea. The Segal method (Segal *et al.* 1959) and Scherrer equation (Burton *et al.* 2009) were used to analyze the relative crystallinity and crystal width of the cellulose in the bamboo culms.

Data Analysis

Analysis of variance (ANOVA) and Duncan's Multiple Range Test were applied to test the significance of vascular bundle density, cell dimension, cell proportion, and crystalline properties of the bamboo culm using IBM SPSS Statistics, Version 21 (IBM, Armonk, USA).

RESULTS AND DISCUSSION

Characteristics of the Vascular Bundle

Figure 1 shows the vascular bundles type of the four bamboo species in *Dendrocalamus* and *Bambusa* genus. *D. asper* and *B. vulgaris* var. *striata* exhibited a type IV vascular bundle, while *D. giganteus* and *B. vulgaris* var. *vulgaris* exhibited a type III vascular bundle. The vascular bundle of bamboo was distinguished into four types based on the central vascular strand pattern and the number of fiber strands (Grosser and Liese 1971). The vascular bundle type III consists of one central vascular strand and one fiber strand. Additional fiber strands were outside the central vascular strand and were distinguishable from vascular bundle type IV from type III.

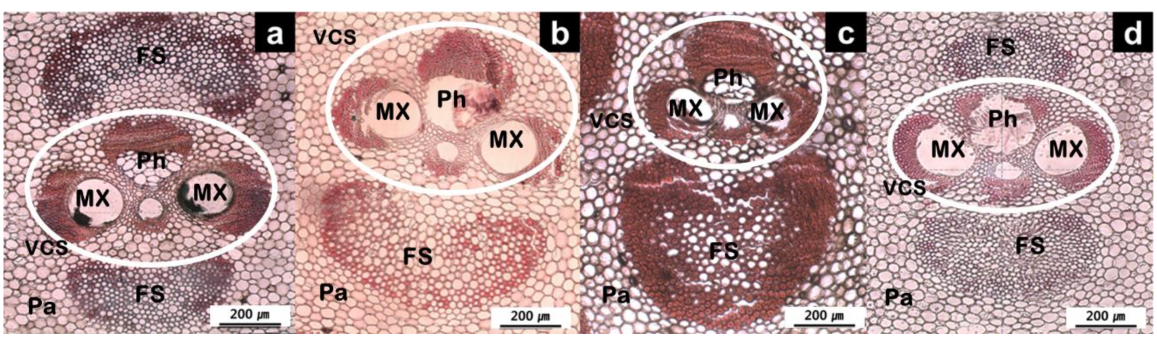

Fig. 1. Vascular bundles in the cross sections of *D. asper* (A), *D. giganteus* (B), *B vulgaris* var. *vulgaris* (C), and *B. vulgaris* var. *striata* (D); VCS: vascular central strand, Pa: parenchyma cells, FS: fiber strand, MX: metaxylem vessels, Ph: phloem

Vascular bundles type III and IV are common in tropical bamboo species and can be found in *Dendrocalamus* and *Bambusa* (Grosser and Liese 1973). These vascular bundles are quite different from the vascular bundle types I and II, which only consist of central vascular strands. Vascular bundle type I was found in subtropical bamboos with leptomorph rhizomes, such as *Phyllostachys pubescens* (Jeon *et al.* 2018b). Sharma *et al.* (2021) found the vascular bundle type II in the bamboos with pachymorph rhizomes such as *Cephalostachyum mannii*. They also suggested that species within the same genus may have different types of vascular bundles. Similar results were reported by Sharma *et al.* (2017) on some *Schizostachyum* species, where Schizostachyum *manii* had vascular bundle type I, while *Schizostachyum pergracile* had vascular bundle type II.

As shown in Table 2, the vascular bundle density was also significantly different among species. *Bambusa vulgaris* var. *vulgaris* had the highest vascular bundle density, while *D. asper* had the lowest. In the radial direction, the vascular bundle densities in the inner parts of the four bamboo species were significantly lower than those in the outer part of the bamboo culm. In the axial direction, the vascular bundle density showed a tendency to increase from the bottom to the top. A similar trend on the variation of vascular bundle density was reported in the bamboo culm of the same genus. Huang *et al.* (2015) reported that the frequency of vascular bundle in *Bambusa rigida* increased from the inner part to the outer part and from the bottom part to the top part. Additionally, a higher vascular bundle concentration in the outer and top parts was found in *Dendrocalamus brandisii* (Wang *et al.* 2016). In our previous study (Maulana *et al.* 2021b), the vascular bundle density in *Gigantochloa* bamboo from Indonesia was higher in the outer part than in the inner part, while there was no variation in the axial direction of the bamboo culm.

Table 2. Vascular Bundle Density in Four Bamboo Species (Unit: umber/4 mm^2)

Species	Outer part				Inner part			
	Top	Middle	Bottom	Mean	Top	Middle	Bottom	Mean
D. asper	17.7 ± 0.82^{b0}	13.4 ± 1.65^{a0}	13.0 ± 1.15^{a0}	14.7 ± 2.48$^{A\ b1}$	3.7 ± 0.48^{b0}	2.7 ± 0.48^{a0}	2.7 ± 0.48^{a0}	3.0 ± 0.67$^{A\ a1}$
D. giganteus	18.0 ± 0.9^{a0}	17.7 ± 1.57^{a0}	17.2 ± 0.92^{a0}	17.6 ± 1.19$^{B\ b1}$	8.1 ± 1.20^{c0}	5.4 ± 0.97^{b0}	4.0 ± 0.47^{a0}	5.8 ± 1.95$^{C\ a1}$
B. vulgaris var. *vulgaris*	25.1 ± 1.10^{b0}	23.9 ± 1.73^{b0}	22.2 ± 1.69^{a0}	23.7 ± 1.91$^{D\ b1}$	8.8 ± 0.92^{c0}	7.7 ± 0.48^{b0}	6.4 ± 0.52^{a0}	7.6 ± 1.19$^{D\ a1}$
B. vulgaris var. *striata*	19.9 ± 1.10^{b0}	19.6 ± 1.84^{b0}	17.0 ± 1.25^{a0}	18.8 ± 1.91$^{C\ b1}$	6.3 ± 0.48^{c0}	5.4 ± 0.52^{b0}	3.1 ± 0.74^{a0}	4.9 ± 1.48$^{B\ a1}$

Notes: Number in the same column followed by different capital letter are different at 5% signify-cance level among species. Numbers in the same row followed by different lower case letter are different at 5% significant level among vertical position (0) and between outer and inner part (1).

Cell Proportion

The cell portions of fiber, parenchyma, and vessel in the four bamboo species are shown in Table 3. There are significant differences found in cell proportion between the genera. *Bambusa* species had a higher fiber proportion and lower parenchyma proportion compared to *Dendrocalamus* species. The vessel proportion in the inner part of the *Dendrocalamus* species was lower than that of the *Bambusa* species. In the outer part, *D. asper* yielded a higher fiber proportion than *D. giganteus*, while there was no significant difference between *Bambusa* species. In the inner part, *B. vulgaris* var. *striata* had a higher fiber proportion than *B. vulgaris* var. *vulgaris*, while there was no significant difference between *D. asper* and *D. giganteus.* The parenchyma proportion in the outer part of *D. asper* was significantly lower than that of *D. giganteus*, while *B. vulgaris* var. *striata* had a higher parenchyma proportion than *B. vulgaris* var. *vulgaris.* In the inner part, *D. asper* had a significantly higher parenchyma proportion than *D. giganteus*, and there was no significant difference between *Bambusa* species. The vessel proportion in the outer part of *D. asper* was significantly higher than that of *D. giganteus*, and *B. vulgaris* var. *striata* yielded a higher vessel proportion than *B. vulgaris* var. *vulgaris*.

The fiber proportion in the outer part of the bamboo culm was higher than that in the inner part, while the parenchyma had higher proportions in the inner section than the outer section. Vessel proportions in the inner part were higher than those in the outer part except for *D. asper*. The vessel proportion increased from the bottom to the top section of the bamboo culm. However, the fiber and parenchyma proportions did not show a fixed trend in the axial direction.

The cell proportions within the bamboo culm in this study were in line with those of the three *Gigantochloa* species (Maulana *et al.* 2021b). The radial variation in the cell proportions could be caused by the radial variations in vascular bundle density. As Huang et al (2015) mentioned, the higher the vascular bundle density in the outer part of the bamboo culm, the lower the parenchyma proportion. In addition, Darwis *et al.* (2020) reported that the vascular bundle percentage of *Gigantochloa pruriens* increased from the inner to the outer part, while the opposite was true for the parenchyma percentage.

Table 3. Cell Portion of the Four Bamboo Species (unit: %)

Species	Position	Fiber		Parenchyma		Vessel	
		Outer	Inner	Outer	Inner	Outer	Inner
D. asper	Top	40 ± 0.32^{A0}	24 ± 0.79^{B0}	52 ± 0.95^{B0}	69 ± 0.88^{A0}	8 ± 0.74^{C0}	7 ± 0.43^{C0}
	Middle	47 ± 1.32^{B0}	21 ± 0.64^{A0}	46 ± 2.22^{A0}	75 ± 0.57^{B0}	7 ± 0.92^{B0}	4 ± 0.32^{B0}
	Bottom	41 ± 2.80^{A0}	23 ± 1.85^{B0}	54 ± 3.46^{B0}	73 ± 2.07^{B0}	5 ± 0.69^{A0}	3 ± 0.41^{A0}
	Average	43 ± 3.77^{B1a}	23 ± 2.00^{A1b}	51 ± 4.16^{C1a}	72 ± 2.95^{C1b}	7 ± 1.49^{BC1b}	5 ± 1.53^{A1a}
D. giganteus	Top	37 ± 2.24^{A0}	22 ± 2.95^{A0}	53 ± 1.90^{AB0}	68 ± 2.57^{A0}	10 ± 0.43^{C0}	10 ± 0.78^{B0}
	Middle	43 ± 0.57^{B0}	24 ± 0.94^{A0}	51 ± 1.08^{A0}	66 ± 1.32^{A0}	6 ± 0.62^{B0}	10 ± 1.30^{B0}
	Bottom	41 ± 2.84^{B0}	24 ± 1.65^{A0}	55 ± 3.21^{B0}	69 ± 1.01^{A0}	4 ± 0.74^{A0}	7 ± 0.94^{A0}
	Average	40 ± 3.20^{A1a}	23 ± 2.08^{A1b}	53 ± 2.67^{D1a}	68 ± 2.07^{B1b}	7 ± 2.59^{AB1a}	9 ± 1.78^{B1b}
B. vulgaris var. *vulgaris*	Top	45 ± 1.35^{AB0}	29 ± 0.49^{B0}	47 ± 2.85^{A0}	58 ± 0.73^{A0}	8 ± 1.51^{B0}	13 ± 0.24^{B0}
	Middle	48 ± 1.32^{B0}	27 ± 1.63^{B0}	46 ± 1.36^{A0}	59 ± 1.21^{A0}	6 ± 0.29^{B0}	13 ± 1.87^{B0}
	Bottom	44 ± 3.40^{A0}	21 ± 2.85^{A0}	52 ± 1.97^{B0}	72 ± 3.68^{B0}	4 ± 1.59^{A0}	7 ± 1.35^{A0}
	Average	46 ± 2.68^{C1a}	23 ± 2.08^{A1b}	48 ± 3.41^{B1a}	63 ± 7.09^{A1b}	6 ± 2.05^{A1a}	11 ± 3.39^{C1b}
B. vulgaris var. *striata*	Top	42 ± 1.69^{A0}	32 ± 2.52^{B0}	49 ± 2.17^{B0}	52 ± 2.09^{A0}	8 ± 0.56^{B0}	15 ± 0.56^{B0}
	Middle	47 ± 2.30^{B0}	23 ± 1.62^{A0}	44 ± 2.37^{A0}	61 ± 1.73^{B0}	8 ± 0.09^{B0}	16 ± 0.20^{B0}
	Bottom	50 ± 2.47^{B0}	24 ± 4.21^{A0}	44 ± 1.94^{A0}	69 ± 3.64^{C0}	6 ± 0.59^{A0}	7 ± 2.10^{A0}
	Average	47 ± 4.00^{C1a}	27 ± 5.13^{C1a}	46 ± 3.16^{A1a}	60 ± 7.36^{A1b}	7 ± 1.45^{C1a}	13 ± 4.39^{D1b}

Notes: Number in the same column followed by different capital letter is different at 5% significance level among vertical position (0) and species (1). Numbers in the same row followed by different lower case letter are different at 5% significant level between outer and inner part for each type of cell.

Cells Dimensions

Table 4 shows the fiber length in the culms of four bamboo species. In the outer part, there was no significant difference between the fiber lengths of *Dendrocalamus* species. In addition, *B. vulgaris* var. *striata* had greater fiber length than *B. vulgaris* var. *vulgaris*. In the inner part, the fiber length was similar between *Dendrocalamus* species, while *B. vulgaris* var. *striata* had greater fiber length than *B. vulgaris* var. *vulgaris*. Moreover, *Dendrocalamus* had longer fibers than *Bambusa*, while *Bambusa vulgaris* var. *vulgaris* had the shortest fiber among the four bamboo species.

The fiber length in the outer part was significantly higher than that in the inner part. A similar trend in the radial direction was reported on the bamboos of *Phyllostachys* (Jeon *et al.* 2018a) and *Gigantochloa* (Maulana *et al.* 2021b). The middle part of the bamboo culm had the longest fiber in the axial direction, except for the inner part of the culm in *B. vulgaris* var. *vulgaris*. In the axial direction, Kumar *et al.* (2015) previously reported that the middle culm of *Bambusa mizorameana* had the longest fiber. On the other hand, the fiber length of *Dendrocalamus brandisii* decreased from the bottom to the top of the bamboo culm (Wang *et al.* 2016).

Table 4. Fiber Length of the four Bamboo Species (Unit: µm)

Species	Outer				Inner			
	Top	Middle	Bottom	Average	Top	Middle	Bottom	Average
D. asper	2325.1 ± 256.5^{a0}	2568.4 ± 369.6^{b0}	2446.2 ± 359.8^{a0}	2446.6 ± 344.5^{Cb1}	2145.7 ± 155.1^{a0}	2406.9 ± 366.8^{b0}	2242.7 ± 362.7^{a0}	2265.1 ± 326.8^{Ba1}
D. giganteus	2316.3 ± 317.7^{a0}	2617.1 ± 328.6^{b0}	2373.1 ± 279.2^{a0}	2435.5 ± 333.5^{Cb1}	2236.2 ± 274.7^{a0}	2433.6 ± 518.1^{b0}	2239.9 ± 326.1^{a0}	2303.2 ± 395.1^{Ba1}
B. vulgaris var. *vulgaris*	2207.3 ± 284.5^{a0}	2352.0 ± 357.8^{b0}	2156.9 ± 328.5^{a0}	2238.7 ± 332.8^{Ab1}	2174.5 ± 281.4^{b0}	2006.5 ± 228.3^{a0}	1982.8 ± 301.6^{a0}	2054.6 ± 283.2^{Aa1}
B. vulgaris var. *striata*	2258.1 ± 250.1^{a0}	2385.7 ± 264.9^{a0}	2371.8 ± 295.9^{a0}	2338.5 ± 274.7^{Bb1}	2254.6 ± 276.6^{a0}	2325.3 ± 267.4^{a0}	2226.6 ± 204.2^{a0}	2268.8 ± 25^{Ba1}

Notes: Number in the same column followed by different capital letter is different at 5% significance level. Number in the same row followed by different lower case letter is different at 5% significance level among vertical position (0) and between outer and inner part (1).

The optical micrographs of the radial and tangential sections in the four bamboo species used for measuring dimensions of vessel and parenchymal cells are shown in Fig. 2. The dimension of the vessel and parenchyma of the four bamboo species are presented in Table 5.

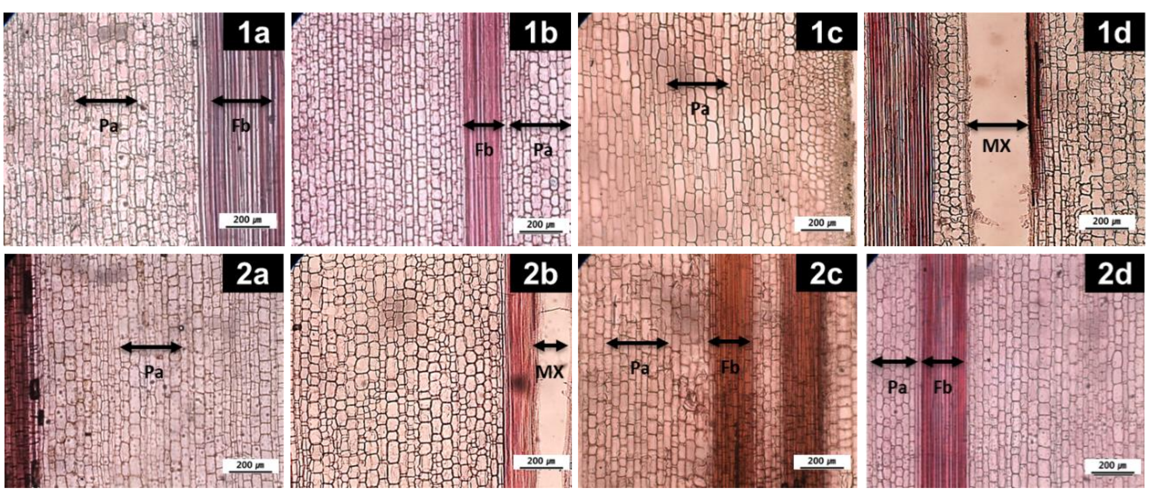

Fig. 2. Optical micrographs of radial (1) and tangential (2) sections of *D. asper* (a), *D. giganteus* (b), *B. vulgaris* var*. vulgaris* (c), and *B. vulgaris* var*. striata* (d). Pa: parenchyma cells, MX: metaxylem vessel, Fb: Fiber bundle

There were significant differences in the vessel diameter and parenchyma dimension between species. *Dendrocalamus giganteus* had the largest vessel and parenchyma diameter, while *B. vulgaris* var. *vulgaris* presented the smallest. Even though they are from the same genus, *B. vulgaris* var. *vulgaris* had the longest parenchyma while *B. vulgaris* var. *striata* had the shortest parenchyma. There was no significant difference in parenchyma length between the tangential and radial sections. Sharma *et al.* (2011) reported that the vessel width in *D. hamiltonii*, *B. tuda*, *B. balcooa*, and *B. aurandacea* from India ranged from 34.4 to 48.4 µm, which are smaller than the values measured in this study. They also reported lower values of parenchyma width and length compared to the results of this study. The vessel diameter in this study was also larger than that of the three *Phyllostachys* bamboos from a subtropical area, ranging from 90.9 to 117.9 µm (Jeon *et al.* 2018a).

Table 5. Dimension of Vessel and Parenchyma of the Four Bamboo Species

Species	Vessel Diameter in the outer part (µm)	Parenchyma Diameter in the outer part (µm)	Parenchyma Length in the outer part	
			Radial	Tangential
D. asper	196.6 ± 36.5^{c}	47.6 ± 5.2^{b}	98.1 ± 27.5^{Ab}	94.5 ± 23.3^{Ab}
D. giganteus	216.8 ± 23.7^{d}	61.1 ± 3.7^{d}	86.1 ± 23.1^{Aa}	80.6 ± 26.3^{Aa}
B. vulgaris var. *vulgaris*	142.9 ± 31.5^{a}	41.2 ± 3.6^{a}	188.7 ± 29.9^{Ac}	203.1 ± 18.1^{Ac}
B. vulgaris var. *striata*	179.8 ± 29.4^{b}	51.7 ± 5.2^{c}	82.1 ± 12.7^{Aa}	82.4 ± 20.8^{Aa}

Notes: Number in the same column followed by different lower case letter are different at 5% significant level. Number in the same row followed by different capital letter is different at 5% significant level.

Crystalline Properties

The relative crystallinity and crystallite width of the four bamboo species are shown in Table 6. There were some differences in the crystalline properties between the bamboo species. *Bambusa vulgaris* var. *vulgaris* showed the highest relative crystallinity and crystallite width, while *D. giganteus* had the lowest values. The crystallite width and relative crystallinity in the inner part were lower than those in the outer part of the culms.

Table 6. Crystalline Properties of the Four Bamboo Species

Species	Position	Relative Crystallinity (%)				Crystallite width (nm)			
		Outer	Mean	Inner	Mean	Outer	Mean	Inner	Mean
D. asper	Top	72	73 ± 2.1^{ABa}	69	69 ± 2.0^{ABa}	3.25	3.28 ± 0.05^{Aa}	3.13	3.20 ± 0.07^{Aa}
	Middle	75		71		3.34		3.26	
	Bottom	71		67		3.26		3.21	
D. giganteus	Top	68	70 ± 2.5^{Ab}	60	63 ± 3.5^{Aa}	3.20	3.20 ± 0.06^{Aa}	2.94	3.10 ± 0.16^{Aa}
	Middle	70		63		3.14		3.10	
	Bottom	73		67		3.26		3.25	
B. vulgaris var. *vulgaris*	Top	76	76 ± 1.0^{Bb}	73	73 ± 0.6^{Ba}	4.17	3.87 ± 0.27^{Ba}	3.96	3.77 ± 0.23^{Ba}
	Middle	75		72		3.63		3.84	
	Bottom	77		73		3.82		3.52	
B. vulgaris var. *striata*	Top	75	74 ± 1.5^{ABa}	69	67 ± 6.1^{ABa}	3.25	3.26 ± 0.07^{Aa}	3.12	3.16 ± 0.09^{Aa}
	Middle	74		73		3.34		3.27	
	Bottom	72		61		3.20		3.10	

Notes: Number in the same column followed by different capital letter is different at 5% significance level. Number in the same row followed by different lower case letter is different at 5% significance level.

The crystalline properties such as relative crystallinity and crystallite width defined the portion and size of crystalline in cellulose, and these properties are essential for species identification and evaluation of bamboo quality. Besides, relative crystallinity was one of the indices that affected the mechanical and physical properties. There are studies that have reported on radial variation in the relative crystallinity and crystallite width of bamboo species. Jeon *et al.* (2018a) reported that the relative crystallinity of three *Phyllostachys* bamboos decreased from the outer part to the inner part. The relative crystallinity and crystallite width in the outer part of three *Gigantochloa* bamboos were also higher than those in the inner part (Maulana *et al.* 2021b). The crystallite width of four bamboo species in this study seemed lower than that in other studies: 5.59 nm in *Dendrocalamus asper* (Fatriasari *et al*. 2014) and 5.70 nm in *Bambusa vulgaris* (Brito *et al.* 2012).

CONCLUSIONS

1. *Dendrocalamus asper* and *Bambusa vulgaris* var. *striata* presented vascular bundle type IV while *D. giganteus* and *B. vulgaris* var. *vulgaris* displayed vascular bundle type III. Vascular bundle density in the bamboo culms increased from the bottom to the top portion and was higher in the outer part than in the inner part.
2. The outer part of the bamboo culm had a higher fiber portion than the inner part, and *vice versa* was observed in the parenchyma portion. The vessel proportion in the inner part of the *Dendrocalamus* species was lower than that of the *Bambusa* species.
3. The fiber length in the outer part of bamboo culm was significantly higher than that in the inner part. *Dendrocalamus* species had longer fibers than *Bambusa* species. *D. giganteus* had the largest vessel and parenchyma diameters, while *B. vulgaris* var. *vulgaris* had the smallest.
4. The outer part of the bamboo culm showed slightly higher relative crystallinity and crystalline width than the inner part.
5. All parameters showed a variation in the radial direction of the of the four bamboo culm but did not show a consistent tendency in the axial direction.
6. Finally, there were significant differences in anatomical characteristics between the bamboo species. It has been suggested that the results of this study could be used for the identification and quality indices of the bamboo species.

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