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Research Article

Assessment of Density and Anatomical Features of Young and Old *Bambusa vulgaris* (*Schrad. ex J.C. Wendl.*) Culm Heights as Sustainable Structural Material in Ghana

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This study sought to assess the density and anatomical features of young and old *Bambusa vulgaris Schrad. ex JC Wendl.* culm heights and, therefore, evaluate their influence on the utilization potential of the culm as a sustainable structural material. *Bambusa vulgaris* culm of 2-year and 4-year-old were harvested and prepared to the required length of 6 meters for the study. Basic density and anatomical features were carried out. The results showed that the basic density of old bamboo ranges from 652.91 kg/m^3 to 729.06 kg/m^3, while the young bamboo ranges from 342.33 kg/m^3 to 509.52 kg/m^3. The vascular bundle arrangement was found to be in Type III and Type IV for the culm heights of both young and old bamboo. The average vascular bundle radial diameter ranged from 761.13 μm to 890.78 μm for the old culm and 727.16 μm to 844.83 μm for the young culm. The average vascular bundle tangential diameter ranged from 499.44 μm to 533.49 μm for the old culm and 425.56 μm to 483.56 μm for the young culm. The radial diameter of the metaxylem vessel of the old culm ranged from 216.81 μm to 54.74 μm, while 214.23 μm to 73.86 μm were for the young culm. Parenchyma tissues ranged from 35%– to 70% for the old bamboo culm and 45% to 75% for the young bamboo culm. Vessel proportion ranged from 6%–12% for the old culm while the young culm ranged from 5%–11%. Fiber proportion ranged from 22% to 54% for the old culm and 19% to 44% for the young culm. Old bamboo had better vascular bundle properties than that of young bamboo. The density is significantly correlated positively to the anatomical properties. Old bamboo is more suitable to be used as the engineered composite material due to its better anatomical features across the culm wall thickness.

1. Introduction

Bamboo is lignocellulosic material known to be a fast-growing species that matures within 3–4 years [1–3]. Bamboo belongs to the family of Gramineae, subfamily of *Bambusoideae*, and the tribe of *Bambuseae* [4–6]. There are approximately 1,662 species of bamboo and 121 genera worldwide [7]. Bamboo grows well in Africa, Asia, and Latin America [8]. Studies have shown that under the right conditions, *Bambusa vulgaris* species display faster rates of growth, which can produce young culms of 3 m to 4 m tall, reaching 20 m height in 3 months [9]. Bamboo is known for providing numerous ecosystem and environmental services such as biodiversity preservation, soil conservation, environmental amelioration, water filtration, and carbon sequestration [10, 11]. It is, therefore, recognized as one of the natural renewable, biodegradable, and recyclable materials proven to have a greater potential in changing the various environmental and economic situations, especially in countries with limited timber resources.

Bambusa vulgaris is the most common bamboo species in Ghana, as it is known as "Green Bamboo," and is commonly found and largely distributed in the southern and middle sectors of the country [12]. This species grows well in deciduous forests, moist evergreen forests, wet evergreen forests, and coastal savannah as it constitutes around 90–95% of the available bamboo resources in the country [13]. Ecologically, there was a higher distribution of bamboo in moist zones (largely moist semideciduous and moist evergreen) than in dry zones (dry semideciduous and savannah) [14]. Furthermore, it is highly visible along the stream and riverbanks as well as in botanical gardens [12]. This species is economically useful, especially in rural communities for housing and fencing, roofing, rice and maize storage facilities, Cocoa mat support, and handicrafts [12].

The use of *Bambusa vulgaris* in the construction industry is gaining popularity in Ghana because its availability coupled with the nonavailability of timber has further justified the usage of both young and old culms [12]. The risk of using young and old culms randomly for structural and nonstructural applications in Ghana without adequate information about the differences in properties is a great concern for industry players [12]. According to [12], both young and old culms will usually exhibit a thicker culm wall, bigger culm diameter, and sometimes uniform internode length. However, these features differ from each other in the determination of strength properties [12]. The knowledge of the material properties could result in its utilization promotion. Studies on the anatomy of bamboo have revealed that across the culm wall, the strength properties change from the inner to the outer layer of the culm [15]. It is also reported that the physical and mechanical properties were correlated to the anatomical properties [16]. It is for these reasons that this study examines the density and anatomical features of young and old *Bambusa vulgaris* culms and, therefore, evaluates their relationship and contribution to the utilization potential of the culm as a sustainable structural material. This will provide valuable fundamental knowledge to aid the utilization of this versatile raw material for various industrial applications, especially in Ghana. In this study, the anatomical features such as vascular bundle type, vascular bundle length, vascular bundle width, metaxylem vessel radial and tangential diameter, and tissue proportion were investigated at different ages and heights of the culm.

2. Materials and Methods

2.1. Collection and Preparation of Culm Samples. *Bambusa vulgaris* culms used for this study were obtained from clumps in Bibiani in the Western North Region of Ghana. Bibiani is located between latitude 3° 6°N and longitude 2° 3°W (moist evergreen forest). The annual rainfall average is between 1200 mm and 1500 mm. The pattern of rainfall is bimodal (March to August and September to October). Humidity is between 75 percent in the afternoon and 95 percent in the nights and early mornings. The culm age was determined based on the features of the culm sheath, the development of branches and leaves, and the external color of the culm. *Bambusa vulgaris* culms of 2-year-old and 4-year-old were randomly selected based on their straightness and culm diameter before harvesting for the study. Six culms were selected from the clump consisting of three 2-year-olds and three 4-year-olds for the study. The culms were cut at 200 mm above ground level and were coated with wax immediately to reduce sap evaporation and prevent fungal and insect attacks. Each culm was cut to a 6-meter height. These culms were later subdivided into three equal lengths of bottom, middle, and top heights of 2 meters each. Wax was applied to coat each height to reduce sap evaporation. The study only focused on the bottom and top heights of the culms for the tests conducted. These culms were sent to the Forestry Research Institute of Ghana (CSIR-FORIG) in Kumasi for further processing, sampling, and subsequent studies.

2.2. Data Collection

2.2.1. Basic Density of Bambusa vulgaris Culm. The basic density (BD) for the *Bambusa vulgaris* culm was determined in accordance with [17]. Samples of 20 mm × 20 mm × culm wall thickness were cut from the culm heights (bottom and top) of the 4-year-old culm and 2-year-old culm, respectively. All 20 replicates were selected from each culm height for the determination of basic density (BD). Samples were initially weighed on a balance with 0.001 g accuracy before sending them in an oven at 103 ± 2°C until attainment of constant weight (g). The samples were then weighed to give the oven-dried weight. The volume of the sample was obtained using the water displacement method. The weight displaced was converted to the volume of the sample as a green volume. The calculation for the basic density was based on the following equation:

$$\text{Basic density}\left(\frac{\text{kg}}{m^3}\right) = \frac{M}{V}, \quad (1)$$

where m is the mass in grams (g) of the test samples oven-dried and v is the green volume of the test samples in mm^3.

2.2.2. Determination of Anatomical Features. Four samples measuring 20 mm cubes were prepared from bottom and top heights for both young and old bamboo culms. The samples were put in a labeled plastic vial containing water for at least 21 days before the water was replaced with an equal part (1 : 1) solution of ethanol and glycerol for at least one week. The softened bamboo samples were heightened with a sliding microtome blade (HM 400, Microm, Walldorf, Germany). Thin heights of approximately 25 μm thickness were cut from the cross-height of the samples. The heights were first washed in distilled water and then stained in 1% safranin. The stained heights were removed and washed with distilled water. The heights were transferred through increasing concentrations of ethanol (30%, 50%, 70% 95%, and 100%) after keeping in each concentration for 15 minutes to slowly take out moisture in the thin heights and to avoid the crumbling. The dehydrated microtome heights were then put in xylene for another 15 minutes to remove little traces of water. Finally, the heights were mounted permanently in Canadian balsam after which the slides were dried in an oven at 60°C for 48 hours.

The determination of the vascular bundle was done by using the prepared slide. Olympus BX41 Microscopic machine (model: BX41TF, Olympus Optical Co. Ltd, Japan) was used to observe the slide at 40x magnification. The focused area was divided into three portions (outer, middle, and inner), and two photograph images per each portion of the culm heights (bottom and top) were taken. In all, six images each were captured for the bottom and top heights of both the young and old bamboo samples. Vascular bundle properties were determined separately for each of the bamboo age and culm heights. For each of the culm heights, 10 vascular bundles were randomly selected from the portions (outer, middle, inner) and measured radially and tangentially with the help of ImageJ 152 Java 8 software. Additionally, 10 metaxylem diameters were randomly selected from each portion (outer, middle, inner) and measured both radially and tangentially with the help of ImageJ 152 Java 8 software to determine the metaxylem vessel diameter.

In addition, tissue proportion was manually determined on the photomicrographs for young and old culms using ImageJ 152 Java 8 software. In determining the proportions of the tissues (parenchyma, vessel, and fiber), the micrographs were inclined at 45° in ImageJ. Thereafter, line scale grids with 30 intersecting points were randomly placed on the micrographs of cross-heights of inner, middle, and outer portions, respectively, for bottom and top heights of young and old bamboo culms. The number of intersects that fell on each particular tissue type was counted using the cell counter in ImageJ. The number of counts obtained by each tissue was expressed as percentages of the total intersecting points of the grid area.

2.3. Statistical Analysis. Statistical analysis was performed using SPSS software version 16.0. Both two-way and three-way factorial analyses with descriptive statistics were mainly used to summarize the results. ANOVA was further used to determine whether there were significant differences among different specimens at $p < 0.05$. Tukey's multiple comparisons of means were used to determine the significant difference between means of portions in radial and tangential diameter as well as tissue proportion in different portions within the heights of the culms at a 5% level of significance.

3. Results and Discussion

3.1. Basic Density of Bambusa vulgaris Culm. Figure 1 indicates the results of the basic density (BD) of bottom and top heights for 4-year-old and 2-year-old *Bambusa vulgaris* culm. The results showed that the BD of 4-year-old bamboo ranges from 652.91 kg/m³ to 729.06 kg/m³, while the 2-year-old bamboo also ranges from 342.33 kg/m³ to 509.52 kg/m³. From the results (Figure 1), the 4-year-old bottom height had a higher basic density compared to the 2-year-old bottom height, with a similar trend of results observed for the top heights. Furthermore, the bottom height across the ages has higher BD values than the top height, respectively. Comparatively, it was observed that the 4-year-old bottom height had a basic density of 729.06 kg/m³,

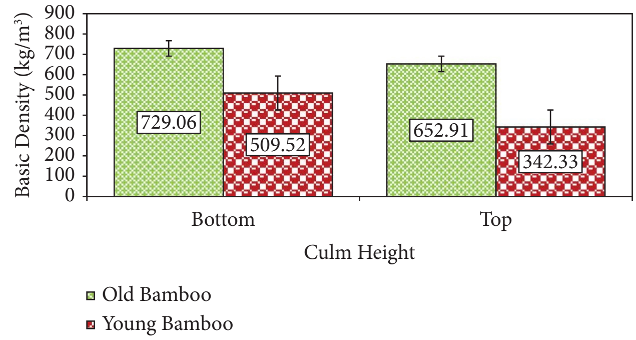


Figure 1: Average basic density of *Bambusa vulgaris* culm; error bars represent the mean standard deviation.

which is 76.15 kg/m³, 219.54 kg/m³, and 386.73 kg/m³ higher than its top height, bottom height, and top height of 2-year old bamboo, respectively. For the *Bambusa vulgaris* species studied, the old (4-year) bamboo culm has higher BD than the young (2-year) bamboo culm (Figure 1). This result is consistent with similar results obtained by Refs. [12, 18–21].

From Figure 1, the variation in BD is influenced by the age and position of the culm. This implies that the BD increases as the culm matures. Additionally, the BD increases as the lateral position of the culm changes from the top height through to the bottom height. In addition, anatomical features such as vascular bundle properties and fiber tissue proportion could also influence the BD variations in the culm. According to Table 1, there is a positive correlation between the BD and vascular bundle length, vascular bundle width, and fiber tissue proportion in that order, and their difference is significant.

The result of ANOVA (Table 2) indicates that at a 5% level of significance, the bamboo age, culm height, and their interaction have a significant effect on the basic density. The level of variability was 95.4%, 81.3%, and 37.8%, respectively, and this could be explained by bamboo age, culm height, and their interactions. This implies that the BD within and across the culm of *Bambusa vulgaris* species is different.

3.2. Vascular Bundle. Figures 2–4 show the anatomical structure of the *Bambusa vulgaris* culm with young and old culms' vascular bundle arrangement from inner, middle, and outer portions for both the bottom and top heights. The results indicate that vascular bundle arrangement for *Bambusa vulgaris* was in type III and type IV, respectively (Figures 3 and 4). Type III consists of the central vascular strand with sclerenchyma sheaths and one isolated fiber bundle, while Type IV consists of the central vascular strand with sclerenchyma sheaths and two isolated fiber bundles. For the 4-year (old) bamboo culm, the bottom height is in type IV (Figures 3 and 4(g)–4(i)), while the top height is in type III (Figures 3 and 4(j)–4(l)), respectively. A similar trend of results was observed for the 2-year (young) bamboo culm (Figures 3 and 4(a)–4(f)). This implies that a full culm of *Bambusa vulgaris* species is a representation of type III and type IV irrespective of age. This result is comparable to similar results as reported by Refs. [22, 23].

Table 1: Correlation matrix for basic density and anatomical features of *Bambusa vulgaris*.

Properties	1	2	3	4	5	6	7	8
(1) BD	1							
(2) VBL	0.466**	1						
(3) VBW	0.410**	0.871**	1					
(4) MRD	0.452**	0.817**	0.909**	1				
(5) MTD	0.509**	0.804**	0.892**	0.986**	1			
(6) PC	−0.310	0.612**	0.778**	0.807**	0.795**	1		
(7) VP	0.127	−0.380**	−0.405**	−0.429**	−0.423**	−0.590**	1	
(8) FP	0.320*	−0.583**	−0.766**	−0.792**	−0.781**	−0.962**	0.347**	1

Note. ** = highly significant at $p < 0.01$, * = significant at $p < 0.05$, ns = not significant; BD = basic density; VBL = vascular bundle length; VBW = vascular bundle width; MRD = metaxylem radial diameter; MTD = metaxylem tangential diameter; PC = parenchyma cell; VP = vessel proportion; FP = fiber proportion.

Table 2: ANOVA for basic density of *Bambusa vulgaris*.

Source	df	F-value	p value	Var. (%)
Bamboo age (BA)	1	1567	0.001**	95.4
Culm height (CH)	1	330.238	0.012*	81.3
BA × CH	1	46.214	0.001**	37.8

Note. ** = significant at $p < 0.01$, * = significant at $p < 0.05$, and ns = not significant.

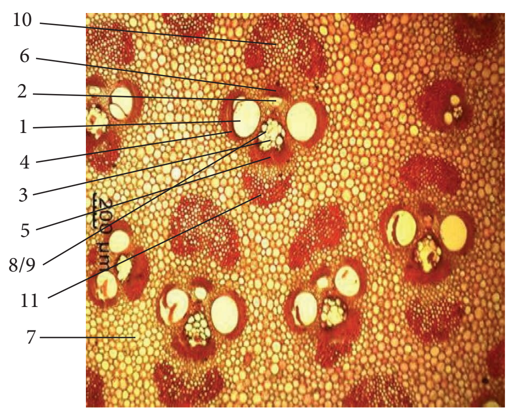
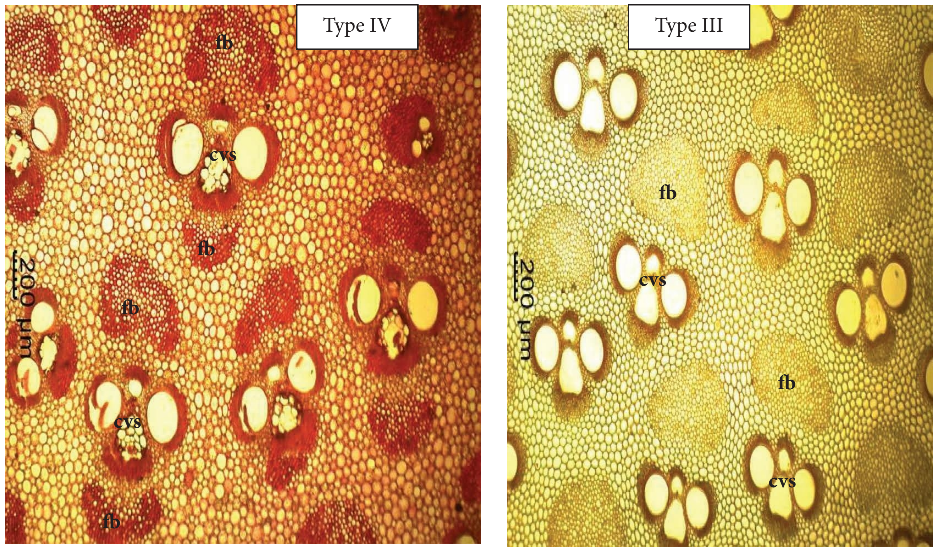


Figure 2: Anatomical structure of the bamboo (*Bambusa vulgaris*) culm. (1) Metaxylem. (2) Protoxylem. (3) Phloem. (4) Side sclerenchyma sheath. (5) Outer sclerenchyma sheath. (6) Inner sclerenchyma sheath. (7) Parenchyma cell. (8) Sieve tube. (9) Companion cell. (10) Inner fiber bundle. (11) Outer fiber bundle.

Again, Figures 3 and 4 show that the type IV vascular bundle improves the fiber quantity in the bottom height of the culm due to the extra fiber bundle compared to type III of the top height. Additionally, as the vascular bundle type (III and IV) changes in size from the inner portion through to the outer portion, the vascular bundle type distribution also increases from the inner to the outer portions of the bottom and top height for both young and old culms as shown in Figures 3 and 4. This implies that the strength properties of culm heights vary across and along the culm wall irrespective of the age difference.

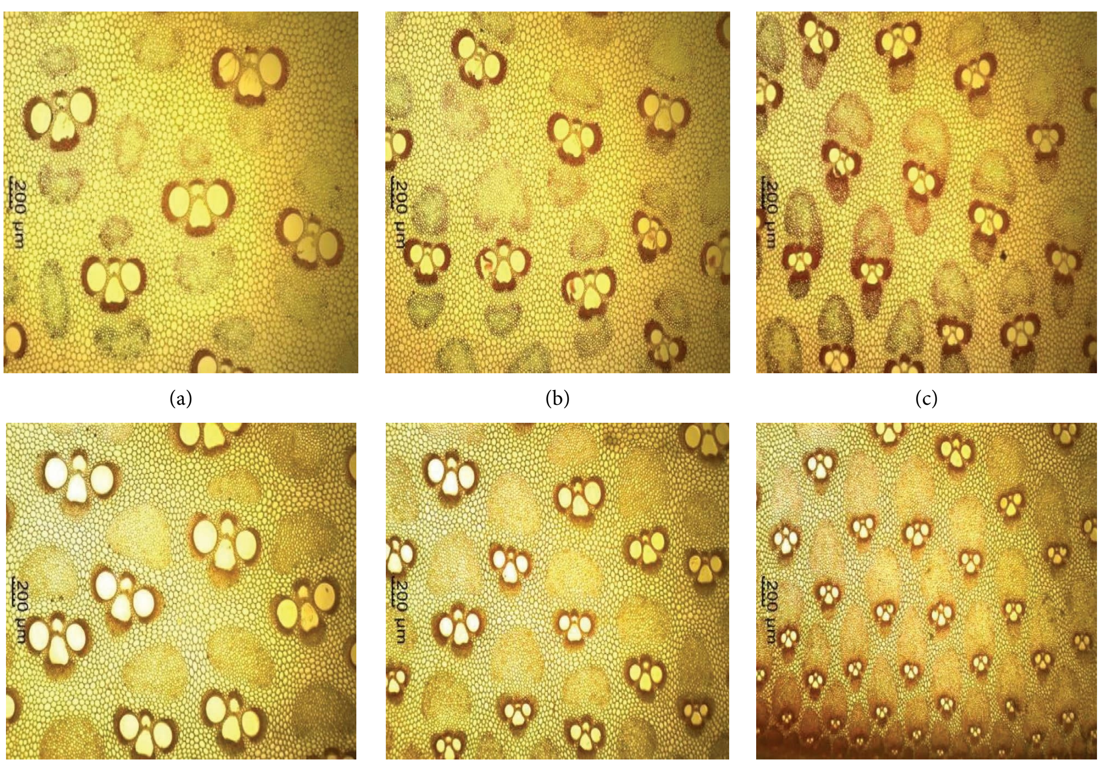
Comparatively, the bottom height dominance of the extra fiber bundle could improve the strength properties compared to the top height of young and old culms. Furthermore, the increase in vascular bundle distribution is highly dense at the outer portions of the bottom and top heights of young and old culms (Figures 4(c), 4(f), 4(i), 4(l)). This implies that the outer portions of young and old bamboo culms will always be stronger than their inner and middle portions, respectively. The authors [1, 24–27] reported a similar trend of results. The literature has shown that the smaller and denser vascular bundle always tends to increase the physical and mechanical properties of the *Bambusa vulgaris* culm as the conductive activities are virtually absent within the outer portion [26, 28].

The result (Figures 2 and 4) further indicates that fibers within the vascular bundle structure are grouped into two (fiber sheaths or sclerenchyma sheaths and fiber bundle). Sclerenchyma sheaths are found to be developed around xylem vessels and phloem tissues as presented in Figures 2 and 4. Additionally, sclerenchyma sheaths developed from the inner portion through to the outer portion, whereas the fiber bundles are always developed inside except for the type IV arrangement, which has an extra fiber bundle developed outside the vascular bundle strand within the vascular bundle structure (Figures 3 and 4).



(a) (b)

Figure 3: Cross section of *Bambusa vulgaris* culm wall with vascular bundles arrangement. Plate (a) is the bottom culm indicating the type IV vascular bundle arrangement made up of one central vascular strand (CVS) with sclerenchyma sheaths and two isolated fiber bundles (fb) inside and outside the central strand. Plate (b) is the top culm indicating the type III vascular bundle arrangement made up of one central vascular strand (CVS) with sclerenchyma sheaths and one isolated fiber bundle (fb) inside the central strand.



(a) (b) (c)

(d) (e) (f)

Figure 4: Continued.

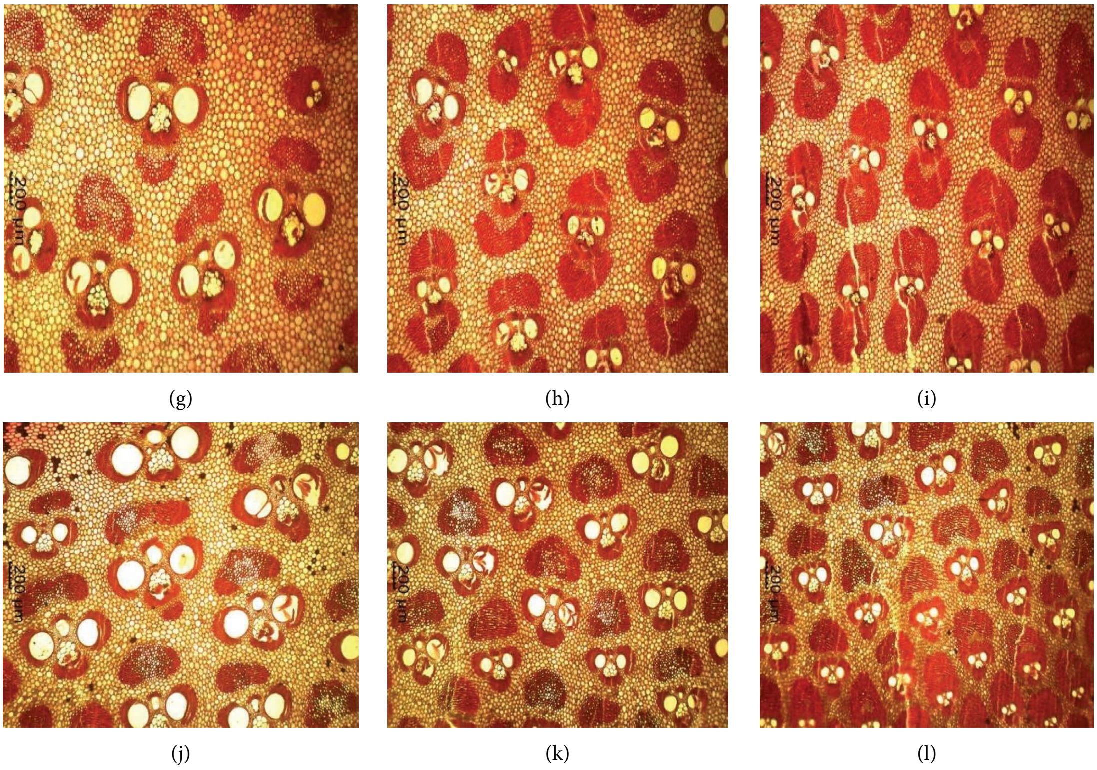


Figure 4: Macrographs of the transverse section of *Bambusa vulgaris* culm wall at different heights; (a–c) inner, middle, and outer portions in the young bottom culm; (d–f) inner, middle, and outer portions in the young top culm; (g–i) inner, middle, and outer portions in the old bottom culm; (j–l) inner, middle, and outer portions in the old top culm. All scale bars represent 200 μm.

Consequently, the extra fiber bundle in type IV perhaps makes the vascular bundle type a key potential influence in the selection of the *Bambusa vulgaris* culm, especially the bottom height as a suitable engineered material for the utilization of structural applications within furniture and building industries [21, 29–32].

3.2.1. Radial and Tangential Diameter of Vascular Bundle. The results as presented in Table 3 show the radial and tangential diameters of the vascular bundle for the bottom and top height of both old and young *Bambusa vulgaris.* From Table 3, the old bottom height had a higher value of 1050.77 μm, 843.37 μm, 778.20 μm and 701.54 μm, 534.43 μm, 364.50 μm for inner, middle, and outer portions, respectively, for radial and tangential vascular bundles compared to the young bottom heights of 968.53 μm, 819.70 μm, 746.27 μm and 627.45 μm, 476.12 μm, 347.10 μm for inner, middle, and outer portions of radial and tangential in that order, respectively. The old top height had a similar trend of results compared to the young top height. Additionally, it can be seen that the old bottom height had the highest value for both radial and tangential diameters of the vascular bundle compared to the inner, middle, and outer portions of the other culm heights.

Comparatively, the radial diameter for the vascular bundle structure of the bottom and top heights of the old bamboo was higher than their corresponding values for the young bamboo. Similar trends of results were obtained for the tangential diameter as well. Furthermore, radial and tangential diameters of the vascular bundle are always longer and wider in the inner portion of the culm compared to the middle and outer portions, respectively. The difference in the radial diameter could be attributed to the number of fiber bundles coupled with the sizes and shapes of protoxylem and phloem and the thickening of sclerenchyma sheath within and outside of the central vascular strand (Figures 2 and 4), while the tangential diameter variation could be due to the metaxylem vessels diameter as well as the thickening of side sclerenchyma sheaths as presented in Figures 2 and 4. This trend of results is comparable to similar findings as reported by the authors of [25, 33]. The study further shows that the radial and tangential diameters vary significantly along the culm heights (bottom to top) for both young and old bamboo as shown in Table 3. This implies that the vascular bundle type largely influenced the variations. This result is consistent with the findings reported by the authors of [34].

According to Figure 4, the radial and tangential diameters contribute significantly to the vascular bundle size determination across the culm wall, which tends to influence the strength properties of the culm, especially density. Table 1 shows that the density correlates positively with radial and tangential diameters of the vascular bundle, with a significant difference between them. It is a foreknowledge that materials' strength properties determine their utilization. Therefore, the utilization potential of the *Bambusa*

Table 3: Mean vascular bundle properties of *Bambusa vulgaris*.

Culm height	Location	Young bamboo culm		Old bamboo culm	
		Vascular bundle radial diameter (μm)	Vascular bundle tangential diameter (μm)	Vascular bundle radial diameter (μm)	Vascular bundle tangential diameter (μm)
Bottom	Inner	968.53 ± 27.22a	627.45 ± 20.95a	1050.77 ± 52.47a	701.54 ± 27.19a
	Middle	819.70 ± 28.22b	476.12 ± 18.71b	843.37 ± 19.64b	534.43 ± 16.83b
	Outer	746.27 ± 19.82c	347.10 ± 18.38c	778.20 ± 26.61c	364.50 ± 18.99c
	Average	844.83 ± 25.09d	483.56 ± 19.35d	890.78 ± 32.91d	533.49 ± 21.00d
Top	Inner	839.28 ± 22.95a	619.87 ± 20.26a	860.14 ± 19.68a	641.13 ± 22.74a
	Middle	710.38 ± 15.67b	396.57 ± 10.15b	776.87 ± 25.51b	516.54 ± 17.19b
	Outer	631.82 ± 18.04c	260.24 ± 12.17c	646.39 ± 28.40c	340.65 ± 11.42c
	Average	727.16 ± 18.89d	425.56 ± 14.19d	761.13 ± 24.53d	499.44 ± 17.12d

Values in columns with the same letters are not significantly different (Tukey's multiple test, $p > 0.05$). ±(SD) signs are standard deviations.

vulgaris culm, especially the bottom heights, could be better than the top heights due to its enhanced vascular bundle properties (Figure 4 and Table 3). Additionally, this could further enhance the acceptability of bottom height for the utilization of bamboo-based composite products in the construction industry [35–39]. Figure 5 indicates the average vascular bundle radial and tangential diameters for both old and young bamboo. Generally, the 4-year bamboo (old) has a longer radial diameter of 39.96 μm and a wider tangential diameter of 61.9 μm than the 2-year bamboo (young) vascular bundle (Figure 5).

The ANOVA results as presented in Table 4 show that at 1% and 5% levels of significance, the bamboo age, culm height, and location have a significant effect on the vascular bundle length and the level of variability was 37.9%, 85.4%, and 93.2%, respectively. This could be explained by the bamboo age, the culm height, and the location. A similar trend was observed by the interaction between the bamboo age, culm height, and location. Similarly, at 1% and 5% levels of significance, the bamboo age, culm height, and location have a significant effect on the vascular bundle width of the *Bambusa vulgaris* species. The level of variability was 76.2%, 63.9%, and 98.3%, respectively, and this could be explained by the bamboo age, culm height, and location. Comparatively, at 1% and 5% levels of significance, the difference between the old bamboo and young bamboo is significant. However, the interaction between the age and culm height is significant at tangential but not at the radial diameter of the vascular bundle. This means that differences within the same bamboo species at different ages could significantly influence vascular bundle diameter. Comparatively, Table 3 indicates that there are significant differences in the vascular bundle diameter within the portions (inner, middle, and outer) studied for the bottom and top heights of young and old bamboo culms. Figure 5 indicates that the vascular bundle diameter increases as the bamboo culm matures.

3.2.2. Metaxylem Vessel Diameter. Table 5 indicates the results of the metaxylem vessel diameter of bottom and top heights for old and young *Bambusa vulgaris* culms. From Table 5, the 4-year (old) bottom height had a better radial diameter compared to the 2-year (young) bottom height, while a similar trend of results was observed for their top heights. Additionally, it was observed that the old bottom height had a radial diameter of 216.58 μm, 137.49 μm, and 54.83 μm for the inner, middle, and outer portions, respectively, compared to the inner, middle, and outer portions of the other heights. Comparing the metaxylem vessel diameter across the culm wall for the bottom and top heights, the 4-year culm had a longer radial diameter than the 2-year culm, especially at the inner and middle portions. However, for both the old and young culm heights, the radial diameter of the outer portion for the bottom height was shorter than their corresponding top height. A similar trend was observed for the tangential diameter (Table 5).

Furthermore, the metaxylem vessel decreases in both radial and tangential diameters across the culm wall from the inner portion through to the outer portion for both young and old culm heights and their difference is significant (Table 5). The variation clearly showed that the vessels' active role in the development of the *Bambusa vulgaris* culm varies across the culm wall and also along the culm heights (Table 5). This result is consistent with similar findings as reported by the authors of [23, 40].

Generally, the metaxylem vessel is usually bigger in the inner portion and decreases as it moves from the inner to outer portions of both young and old bamboo culms. This could be attributed to the natural growth of the culm structure as its main function is for water and nutrient transportation [28, 40]. Perhaps, this phenomenon could have accounted for or best explained why shrinkage and swelling are always more visible at the inner portion than the outer portion. Furthermore, the metaxylem vessel diameter is always seen as a dead vessel at the outer portion, especially at the periphery of the culm wall (Figure 4 and Table 5).

Figure 6 shows the average metaxylem radial and tangential diameters for both old and young bamboo. The 4-year (old) bamboo has a longer radial diameter of 16.93 μm and a wider tangential diameter of 18.33 μm than the 2-year (young) bamboo metaxylem diameter (Figure 6). Figure 6 indicates that the metaxylem diameter increases as the bamboo culm matures.

Table 6 shows the ANOVA results such that at 1% and 5% levels of significance, the bamboo age, culm height, and vessel location have a significant effect on the metaxylem

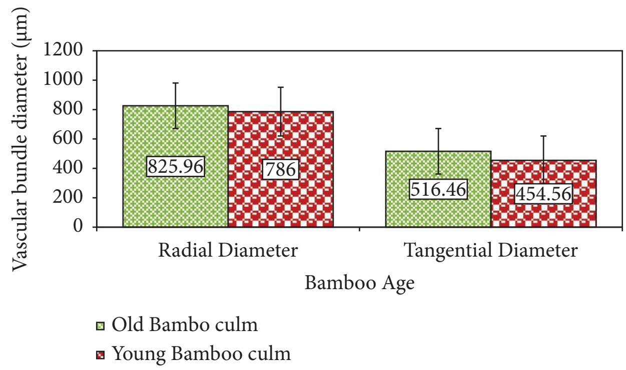


Figure 5: Average vascular bundle of the *Bambusa vulgaris* culm.

Table 4: ANOVA vascular bundle radial and tangential of *Bambusa vulgaris*.

Source	df	Vascular bundle radial			Vascular bundle tangential		
		F-value	p-value	Var. (%)	F-value	p-value	Var. (%)
Bamboo age (BA)	1	65.905	0.001**	37.9	345.484	0.001**	76.2
Culm height (CH)	1	631.186	0.001**	85.4	190.939	0.001**	63.9
Location (L)	2	735.564	0.001**	93.2	3067	0.001**	98.3
BA × CH	1	1.479	0.227ns	1.4	12.922	0.001**	10.7
BA × L	2	3.027	0.053*	5.3	16.721	0.001**	23.6
CH × L	2	17.848	0.001**	24.8	3.591	0.031*	6.2
BA × CH × L	2	9.413	0.001**	14.4	33.219	0.001**	38.1

Note. **significant at 1% probability level; *significant at $p < 0.05$; ns: not significant.

Table 5: Metaxylem vessel diameter in different locations of *Bambusa vulgaris*.

Culm height	Location	Old bamboo culm		Young bamboo culm	
		Radial diameter (μm)	Tangential diameter (μm)	Radial diameter (μm)	Tangential diameter (μm)
Bottom	Inner	216.58 ± 8.22a	198.06 ± 4.64a	214.42 ± 2.56a	173.95 ± 8.97a
	Middle	137.49 ± 3.36b	119.97 ± 3.34b	118.44 ± 2.38b	102.97 ± 3.24b
	Outer	54.83 ± 3.04c	39.07 ± 2.53c	73.88 ± 1.90c	67.09 ± 3.11c
	Average	136.30 ± 4.87d	119.03 ± 3.50d	135.58 ± 2.28d	114.67 ± 5.11d
Top	Inner	214.22 ± 3.59a	190.72 ± 5.70a	144.17 ± 5.30a	116.35 ± 2.91a
	Middle	134.78 ± 5.39b	114.47 ± 2.99b	104.45 ± 3.72b	99.97 ± 1.95b
	Outer	65.49 ± 2.32c	59.48 ± 3.22c	87.13 ± 1.86c	72.20 ± 2.27c
	Average	138.16 ± 3.77d	121.56 ± 3.97d	111.92 ± 3.63d	96.17 ± 2.38d

Values in columns with the same letters are not significantly different (Tukey's multiple test, $p > 0.05$). ±(SD) signs are standard deviations.

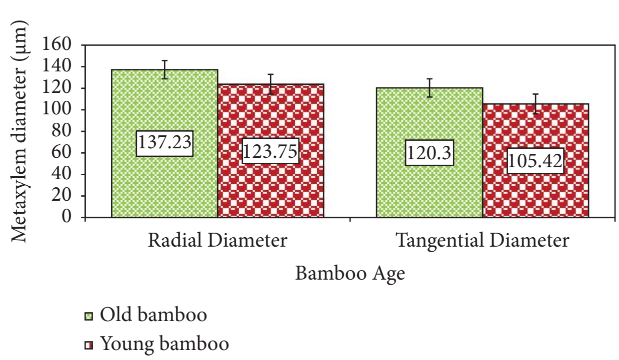


Figure 6: Average metaxylem diameter of the *Bambusa vulgaris* culm.

radial diameter. Their level of variability was 75.5%, 66.8%, and 99.5%, respectively, and this could be explained by the bamboo age, culm height, and vessel location. Similar trends of results were observed for all the interactions between the bamboo age, culm height, and vessel location. Comparatively, at 1% and 5% levels of significance, the difference

Table 6: Analysis of variance for metaxylem vessels' diameter of *Bambusa vulgaris*.

Source	df	Radial diameter			Tangential diameter		
		F-value	p value	Var. (%)	F-value	p value	Var. (%)
Bamboo age (BA)	1	333.020	0.001**	75.5	381.509	0.001**	77.9
Culm height (CH)	1	217.728	0.001**	66.8	110.022	0.001**	50.5
Vessel location (VL)	2	9933	0.001**	99.5	7016	0.001**	99.2
BA × CH	1	298.392	0.001**	73.4	190.456	0.001**	63.8
BA × VL	2	544.076	0.001**	91	696.648	0.001**	92.8
CH × VL	2	358.449	0.001**	86.9	299.893	0.001**	84.7
BA × CH × VL	2	212.771	0.001**	79.8	103.555	0.001**	65.7

Note. **significant at 1% probability level; ns: not significant.

between the 2-year bamboo and 4-year bamboo is significant. Furthermore, their interactions between the age and culm height are significant at both radial and tangential of the metaxylem diameter. This means that differences within and across the culm age and height could significantly influence the metaxylem diameter. Additionally, Table 5 indicates that the differences in the metaxylem radial diameter for the inner, middle, and outer portions were significant within the culm heights of the bamboo ages. Similarly, the results as presented in Tables 5 and 6 indicate that the metaxylem tangential diameter is not different from the trend of the radial diameter results. Comparatively, Tables 5 and 6 show that the significant difference in the metaxylem diameter is always visible within the portions (inner, middle, and outer) and along the culm heights of 2-year and 4-year *Bambusa vulgaris*. This suggests that the portion, height, and age of the bamboo culm significantly influence the variations in the metaxylem diameter.

3.3. Tissue Proportion

3.3.1. Parenchyma Cell. Figure 7 shows the parenchyma tissue proportion in different locations of the bottom and top heights for both young and old *Bambusa vulgaris*. The percentage of parenchyma tissues proportion ranged from 35% to 70% for the old bamboo culm, while the young bamboo culm ranged from 45 to 75%. From Figure 7, the 2-year (young) bottom height had 7.67% higher parenchyma tissue compared to the 4-year (old) bottom height. A similar trend of result was observed for the top heights. Additionally, it was observed that the young top height had the highest percentage proportion of parenchyma tissue of 75%, 61%, and 48% for inner, middle, and outer portions in that order compared to the inner, middle, and outer portions of the other heights. Furthermore, the young bamboo had a higher proportion of parenchyma tissues in the bottom and top heights than its corresponding percentage for the old bamboo. The results further showed that, for both the old and young bamboo, the proportion of parenchyma tissues at the top height was more than its corresponding bottom height. A similar trend was observed for the old bamboo. This suggests that the top heights contained more parenchyma tissues than the bottom heights of the *Bambusa vulgaris* species.

The result of the study is comparable to similar findings reported by the authors of [41]. Their study reported that parenchyma tissues found in the inner height and outer height were 63.73% and 31.76% for *Bambusa* species, 52.82% and 33.62% for *Bambusa vulgaris* var. *striata*, 54.32% and 33.76% for *Bambusa vulgaris Schrad*, and 58.19% and 33.64% *Oxytenanthera abyssinica Munro*, respectively. Studies have shown that the parenchyma tissue constitutes about 50–52% of the total culm tissues [42–45]. However, the result of the study shows that the parenchyma proportion ranges from 35% to 75% for the *Bambusa vulgaris* species, which is slightly higher compared to the above studies.

Comparatively, Figure 7 shows that the inner portion across the culm wall has more parenchyma tissues than that of the middle and outer portions. A similar finding was reported by the authors of [34]. This implies that the inner portion of both young and old bamboo culms contained a higher carbohydrate content than that of the middle and outer portions. The high content of parenchyma tissues in the inner and middle portions could affect the service life of the *Bambusa vulgaris* culm since organisms such as molds, fungi, and termites do feed on starch granules found in parenchyma cells [1, 46].

Consequently, this will always influence the selection of *Bambusa vulgaris* species as potential utilization for structural applications, because it could affect the natural durability of the culm negatively if not treated. According to [47], the carbohydrate content of bamboo plays an important role in its service life. This suggests that the service life of *Bambusa vulgaris* species is solely dependent on the preservation chemicals [47, 48] used for treatment. This implies that both young and old bamboo culms could be susceptible to termite, fungal, and beetle attacks since these biodegradable agents feed on the carbohydrates found in the parenchyma cells [47].

Figure 8 shows the average parenchyma proportion for both old and young bamboo. The 2-year (young) bamboo contains 7.34% higher parenchyma proportion than the 4-year (old) bamboo (Figure 8). Figure 8 indicates that the parenchyma cell always decreases in proportion as the bamboo culm matures.

Comparatively, Table 7 indicates that there are significant differences in the parenchyma tissue among the portions (inner, middle, outer) studied for the bottom and top heights of young and old bamboo culms. Figures 7 and 8 indicate that the parenchyma tissue increases in the young stage and decreases as it matures. This was more visible in the top height than the bottom height even in young and old

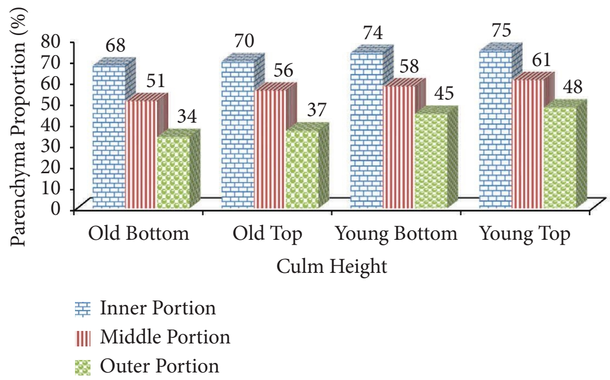


Figure 7: Average parenchyma proportion in the portions of *Bambusa vulgaris* culms.

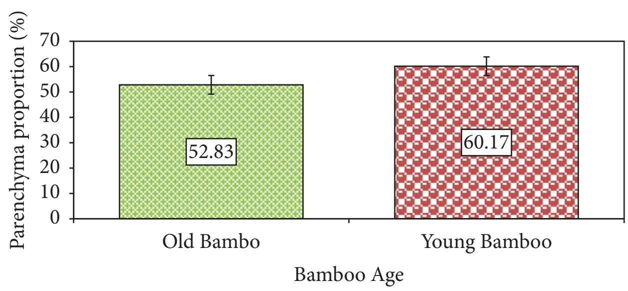


Figure 8: Parenchyma proportion for *Bambusa vulgaris* culm.

Table 7: Tissue proportions of *Bambusa vulgaris*.

Tissues	Location	Old bamboo culm		Young bamboo culm	
		Bottom	Top	Bottom	Top
Parenchyma (%)	Inner	68 ± 0.50a	70 ± 1.58a	74 ± 0.84a	75 ± 0.71a
	Middle	51 ± 0.84b	56 ± 1.64b	58 ± 0.89b	61 ± 0.45b
	Outer	35 ± 0.71c	37 ± 0.55c	45 ± 0.71c	48 ± 0.55c
	Average	51.33 ± 0.68	54.33 ± 1.26	59 ± 0.83	61.33 ± 0.57
Vessel (%)	Inner	6 ± 0.50a	8 ± 0.55a	5 ± 0.71a	6 ± 0.84a
	Middle	10 ± 0.71bc	11 ± 0.84bc	9 ± 0.84bc	8 ± 0.55bc
	Outer	11 ± 0.84bc	12 ± 0.55bc	11 ± 0.84bc	10 ± 1.00bc
	Average	9 ± 1.49	10.33 ± 0.65	8.33 ± 0.80	8 ± 0.80
Fiber (%)	Inner	26 ± 0.82a	22 ± 1.04a	21 ± 0.84a	19 ± 0.45a
	Middle	39 ± 0.84b	33 ± 1.34b	33 ± 0.55b	31 ± 0.45b
	Outer	54 ± 1.10c	51 ± 0.84c	44 ± 1.10c	42 ± 0.55c
	Average	39.67 ± 0.92	35.33 ± 1.07	32.67 ± 0.83	30.67 ± 0.48

Values in columns of parenchyma, vessel, and fiber with the same letters are not significantly different (Tukey's multiple test, $p > 0.05$). ±(SD) signs are standard deviations.

levels (Figure 7). However, the higher proportion of the parenchyma tissue did not influence the density of the culm as it correlates negatively (Table 1).

The results of ANOVA as indicated in Table 8 show that at 1% and 5% levels of significance, the bamboo age, culm height, and tissue location have a significant effect on parenchyma cells' proportion and their level of variability was 43.6%, 8.8%, and 90.2%, respectively. Comparatively, at 1% and 5% levels of significance, the difference between the 2-year bamboo and 4-year bamboo is significant. This means that differences within the culm age and height could significantly influence the parenchyma proportion. This implies that the parenchyma cell proportions are very visible along the culm heights and ages of *Bambusa vulgaris* species.

3.3.2. Vessel Proportion. Figure 8 shows the results of the vessel proportion in different locations for the bottom and top heights of both young and old *Bambusa vulgaris*. The percentage of vessel proportion ranged from 6% to 12% for the old bamboo culm, while the young bamboo culm ranged from 5% to 11%. For all the heights of the *Bambusa vulgaris* species studied for the vessel proportion, the old top height

Table 8: ANOVA for tissue proportion of *Bambusa vulgaris*.

Source	df	Parenchyma			Vessel			Fiber		
		F-value	p value	Var. (%)	F-value	p value	Var. (%)	F-value	p value	Var. (%)
Bamboo age (BA)	1	36.293	0.001**	43.6	2.492	0.121ns	5	24.370	0.001**	34.1
Culm height (CH)	1	4.512	0.039*	8.8	0.220	0.641ns	0.5	6.830	0.012*	12.7
Tissue location (TL)	2	217.084	0.001**	90.2	7.882	0.001**	25.1	169.727	0.001**	87.8
BA × CH	1	0.030	0.863ns	0.1	0.657	0.422ns	1.4	0.759	0.388ns	1.6
BA × TL	2	1.946	0.154ns	7.6	0.091	0.913ns	0.4	2.826	0.069ns	10.7
CH × TL	2	0.477	0.624ns	2	0.216	0.807ns	0.9	0.192	0.826ns	0.8
BA × CH × TL	2	0.135	0.874ns	0.6	0.045	0.956ns	0.2	0.192	0.826ns	0.8

Note. **significant at $p < 0.01$; *significant at $p < 0.05$; ns: not significant.

recorded the highest percentage value of 8%, 11%, and 12% for inner, middle, and outer portions, respectively than that of the inner, middle, and outer portions of other heights. Additionally, the old bamboo had more vessels located at the bottom and top heights than the young bamboo.

Comparatively, Figure 9 shows that the outer portion of the culm wall has more vessels than the middle and inner portions. However, Table 7 indicates that the number of vessels found in the inner portion has significant differences when compared to the middle and outer portions, while the vessel proportions between the middle and outer portions are not significant to each other. Some studies suggested that conducting tissues (vessels and sieve tubes) constitute about 8–10% of the total culm tissues [42–45]. However, the result (Figure 9) of this study shows otherwise as the vessel proportion for the *Bambusa vulgaris* species is slightly higher than the above studies. This suggests that within the culm wall of *Bambusa vulgaris* species, there are variations in the anatomical features.

Figure 10 indicates the average vessel proportion for both old and young bamboo. The 4-year (old) bamboo contains a 1.50% higher vessel proportion than the 2-years (young) bamboo (Figure 10). Figure 10 shows that the vessel increases in the proportion as the bamboo culm matures. The results of ANOVA as indicated in Table 8 show that at a 5% level of significance, the tissue location has a significant effect on the vessel proportion and the level of variation was 25.1%. This implies that the vessel proportions are very visible within the culm wall of the *Bambusa vulgaris* species. Comparatively, at 1% and 5% levels of significance, the difference between the 2-year bamboo and 4-year bamboo is not significant. This means that differences within the culm age and height could not influence vessel proportion significantly. Comparatively, Table 7 further indicates that there are no significant differences in vessel proportion within the portions (inner, middle, outer) studied for the bottom and top heights of young and old bamboo culms.

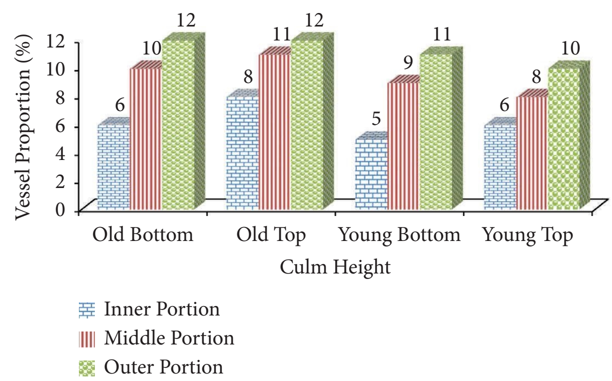


Figure 9: Average vessel proportion in the portions of *Bambusa vulgaris* culms.

3.3.3. Fiber Proportion. The results of the measurement of the fiber proportion in different locations for the bottom and top heights of both young and old *Bambusa vulgaris* are shown in Figure 11. The fiber tissue proportion ranged from 22% to 54% for the old bamboo culm, while the young bamboo culm ranged from 19% to 44%. The results further indicate that the old bottom height had higher fiber tissue proportion compared to the young bottom height, while the old top height had a similar trend of result compared to the young top height.

According to Figure 11, the old bottom height had the highest fiber proportion of 25%, 39%, and 54% with the young top height recording the lowest fiber proportion of 19%, 31%, and 42% for inner, middle, and outer portions in that order for all heights, respectively. Furthermore, it was observed that in the *Bambusa vulgaris* species studied for the fiber proportion, the old bamboo was higher than that of the young bamboo for the bottom and top heights. Comparatively, the fiber tissues saw an increase from the inner portion through to the outer portion of all the heights for both young and old culms. This higher and visible proportion of the fiber is due to the general structure of the bamboo culm, which reveals that the inner portion contains more parenchyma cells but fewer fibers and conducting cells than in the outer portion of the culm wall [1]. Additionally, the difference could be attributed to age. The result shows that fiber proportion increases as the culm matures (Figure 11). Additionally, Table 7 indicates that there are significant differences in fiber proportions that occurred between the inner, middle, and outer portions.

Studies revealed that fiber tissue constitutes about 40% of the total culm tissues [42–45]. Comparatively, the result of this study for the *Bambusa vulgaris* species indicates otherwise as the average mean of the fiber proportion ranges

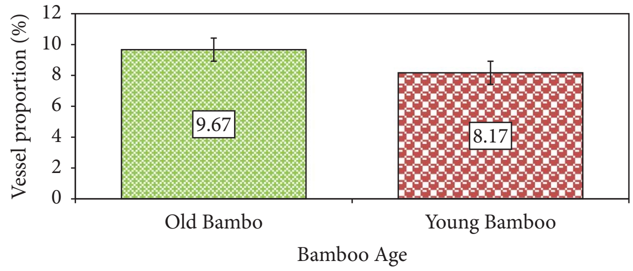


Figure 10: Vessel proportion for *Bambusa vulgaris* culm.

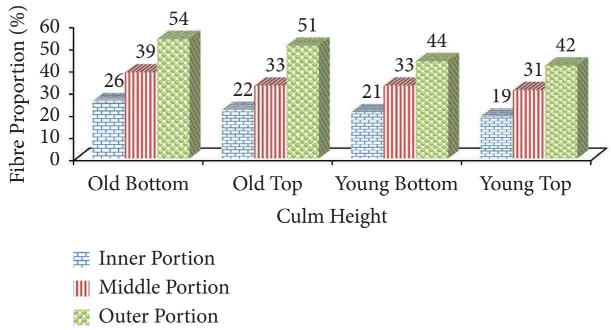


Figure 11: Average fiber proportion in the portions of *Bambusa vulgaris* culms.

from 19% to 54%. This implies that the increase in the fiber proportion could have a greater potential of improving the physical properties, especially density. From Table 1, fiber proportions significantly correlate positively with density. Additionally, the fiber plays a key role in providing the bamboo material with strength and toughness [49, 50]. This implies that the proportion of fiber tissues within the heights of the *Bambusa vulgaris* culm, especially the bottom height, could enhance its utilization for the manufacturing of engineered composite products such as fiber-medium boards, laminated boards, particleboards, and bamboo-ply [35–38].

Figure 12 indicates the average fiber proportion for both old and young bamboo. The 4-year (old) bamboo contains 5.83% higher fiber proportion than the 2-year (young) bamboo (Figure 12). Figure 12 indicates that the fiber proportion increases as the bamboo culm matures. The result of ANOVA (Table 8) indicates that at 1% and 5% levels of significance, the bamboo age, culm height, and tissue locations have a significant effect on the fiber proportion. The level of variability was 34.1%, 12.7%, and 87.8%, respectively, and this could be explained by the bamboo age, culm height, and location. Comparatively, at 1% and 5% levels of significance, the difference between the 2-year bamboo and 4-year bamboo is significant. This means that differences within the culm age and height could significantly influence the fiber proportion. Comparatively, Table 7 indicates that there are significant differences in the fiber proportion within the portions (inner, middle, outer) studied for the bottom and top heights of 2-year and 4-year bamboo culms. This implies that the fiber proportions are very visible within and across the culm wall thickness of Bambusa vulgaris species.

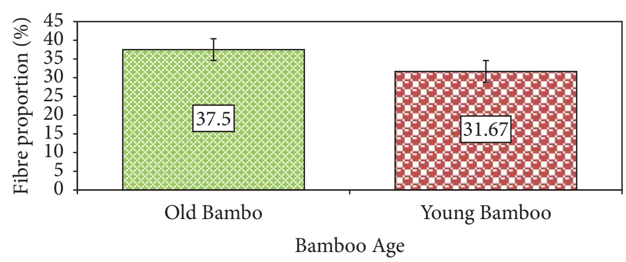


Figure 12: Fiber proportion for *Bambusa vulgaris* culm.

4. Conclusion

The assessment of density and anatomical features of young and old *Bambusa vulgaris* culm heights were investigated. The *Bambusa vulgaris* culm contained two vascular bundle arrangements, type III for the top height and type IV for the bottom height regardless of age. In addition, the vascular bundle tends to be smaller, denser, and more at the outer portion than the middle and inner portions of *Bambusa vulgaris* culms. It could be further concluded that the old bamboo culm contained higher radial and tangential diameters than those of the young bamboo culm. Additionally, the old bamboo culm contained a better metaxylem vessel diameter than that of the young bamboo culm. Furthermore, the metaxylem vessel diameter for the old bamboo culm was smaller at the outer portion than the young bamboo culm. The metaxylem vessel diameter decreases from the inner portion through to the outer portion of the *Bambusa vulgaris* culms. The differences in the metaxylem vessel diameter were significant.

The study further concluded that the top heights contained more parenchyma tissues than the bottom heights of the *Bambusa vulgaris* species. Furthermore, the inner portion contained the highest percentage of parenchyma tissues followed by the middle and outer portions in that order for the *Bambusa vulgaris* species. Additionally, parenchyma tissues decrease as the *Bambusa vulgaris* species matures. It could be further concluded that the outer portions of the culm contained more vessels than the other two portions (middle and inner). Furthermore, the old bamboo contained a higher amount of fiber proportion than the young bamboo culm, especially at the bottom height. The density correlates positively to all anatomical features studied except parenchyma and vessel proportions, respectively, and the differences are significant.

On the whole, the old bamboo culm of *Bambusa vulgaris* possesses overall better density and anatomical features than the young bamboo culm. Therefore, the old *Bambusa vulgaris* is more suitable to be used as the engineered composite material than the young, which is wealthy to be considered a sustainable structural material.

Data Availability

All the data will be available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed to the study's conception and design. Michael Awotwe-Mensah contributed to material preparation, contributed to data collection, performed analysis, and wrote the original draft. Stephen Jobson Mitchual and Emmanuel Appiah-Kubi reviewed and edited the manuscript. All authors have read and approved the final manuscript for submission.

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