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Fishpole Bamboo [*Phyllostachys aurea* (Andre) Riviere and C. Riviere] in the Philippines: Its Properties and Potential Utilization

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This study focused on assessing the morphological, anatomical, and physico-mechanical properties of fishpole bamboo [*Phyllostachys aurea* (André) Rivière and C.Rivière] grown in Baguio City, the Philippines. The aim of this study was to establish baseline information about these properties and recommend potential applications beyond ornamental use. The results showed that the relative density, modulus of rupture, and stress at the proportional limit of the fishpole bamboo were higher than those of commercial bamboo species. In terms of morphological properties, the culm diameter and culm wall thickness tended to decrease significantly by 64.0 and 39.96%, respectively, toward the top portion. In contrast, the internode length increased significantly from bottom to middle by 41.57%. With respect to anatomical properties, the fiber length, fiber and lumen diameter, and cell wall thickness significantly decreased from bottom to top by 14.89, 13.63, 23.32, and 10.67%, respectively. Conversely, its relative density and radial shrinkage significantly increased by 23.06% and 26.77%, respectively, toward the top. Regarding the mechanical properties, the modulus of rupture, stress at the proportional limit, and modulus of elasticity increased significantly by 62.41, 88.25, and 45.51% from the bottom of the culm to the top, respectively. However, the compressive strength (29.40 MPa) and shear strength (2.83 MPa) deviated from this trend. Fishpole bamboo can be employed as a raw material for furniture, window frames, and handicrafts, wherein a large diameter is not required. Additionally, it can be used for canes, walking sticks, umbrella and fan handles, and souvenir materials. Notably, culms with diameters exceeding 5.0 cm can be used as raw materials for laminated and engineered bamboo. They can also be used as raw materials for preparing pellets and briquettes.

Keywords: anatomical, fishpole bamboo, mechanical, *Phyllostachys aurea*, physical

INTRODUCTION

Fishpole bamboo also known as running bamboo and golden bamboo [*Phyllostachys aurea* (André) Rivière and C. Rivière] is a monopodial species native to China and Vietnam, and introduced to the Philippines (Roxas 2012). It is characterized by its erect culms, which can reach heights of 2.0–12.0 m, with a diameter ranging from 2.0–9.0 cm and 4.0–8.0 mm thick. Its versatility and aesthetic appeal have led to its introduction in numerous countries worldwide, even in temperate regions (Roxas *et al.* 2000).

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Thriving in bamboo-rich forest areas, fishpole bamboo is also extensively planted along roadsides, backyards, and parks in Baguio City, primarily for its ornamental value. The Department of Environment and Natural Resources–Ecosystems Research and Development Bureau (DENR-ERDB) recognizes its beauty and utility, and as a result, has included it in the list of recommended ornamental bamboos for urban parks (Roxas *et al.* 2000). It also holds a prominent place in one of Baguio's famous tourist attractions – the St. Francis Xavier Seminary Bamboo Educational Demo Farm, also known as the Bamboo Sanctuary (Elias 2022). Fishpole bamboo's ability to enhance green spaces and add natural charm to urban environments makes it an attractive choice for landscaping and beautification projects.

In Spain (Elejoste *et al.* 2022) and Brazil (Seixas *et al.* 2022), fishpole bamboo was characterized by a height ranging from 6.0–9.0 m, diameters between 3.0–5.0 cm, and a culm density of 0.863. Its compression strength was 71.4 MPa, whereas its bending strength was 4.09 GPa. Notably, there was a noticeable increase in the proportion of sclerenchyma cells (22.22%) and vascular bundles (44.44%) toward the top of the culm. Conversely, the parenchyma cells exhibited a declining trend (29.26%). Moreover, in Brazil, this bamboo is not only used as an ornamental species but also as a raw material. Bamboo culms aged between 3–7 yr are processed to create durable and sustainable modular panels (Barata *et al.* 2023). This application showcases fishpole bamboo's potential as a construction material.

Rusch *et al.* (2019) reported that fishpole bamboo is also used for laminated bamboo in Brazil. The laminated bamboo made from fishpole bamboo has an equal density and comparable modulus of elasticity with panels made from giant bamboo (*Dendrocalamus asper*). However, its modulus of rupture, shear strength, and hardness are significantly lower than the latter. Despite these differences, fishpole bamboo remains suitable for producing laminated bamboo panels.

Fishpole bamboo is primarily used as an ornamental plant in the Philippines, mainly due to the limited information available about its crucial properties such as morphological, anatomical, and physico-mechanical aspects. These key characteristics play a significant role in determining the species' broader utilization. This study is a pioneering effort aimed at determining the fundamental properties of fishpole bamboo and exploring its potential value-added applications. The results would not only enhance the use of the ornamental fishpole bamboo but also offer additional alternative species choices for farmers and bamboo product producers.

METHODOLOGY

Sample Preparation and Testing

Six mature culms of fishpole bamboo collected from different clumps with ages between 4–5 yr old were gathered from Loakan, Baguio City (Figure 1). The age was determined following the description of Santos (2018). The collecting sites were located at 1,570 m above sea level (asl), with temperatures averaging between 18–26 ºC. The culms were gathered at around 30 cm above the ground. Each length of the culm was precisely measured. The culms were then cut into three equal portions – labeled bottom, middle, and top. Figure 2 illustrates the sampling procedure employed to obtain samples from the culms of fishpole bamboo.

A culm sample ring 20 mm long was collected from the nodes and internodes of each portion. These samples were used to determine the anatomical properties. For assessing the physical properties, samples 125 mm long were collected from the static bending samples of each portion. These samples were used to determine the moisture content, relative density, and shrinkage properties. Additionally, two sets of samples were prepared to assess compression strength and shear strength – namely, samples with nodes and samples without nodes.

Morphological Properties

Six culms of fishpole bamboo were used to determine the morphological properties. The method of Razak *et al.* (2012) was used to measure the length of the internodes. Moreover, the diameter of the bamboo was determined by calculating the average of two perpendicular measurements across opposing points on the outer culm surface. To gauge the culm wall thickness, four measurements were taken around the culm circumference using a vernier caliper, spaced at 90° intervals (ISO 22157:2019).

Anatomical Properties

Fiber dimensions were assessed using the method described by Espiloy *et al.* (1999). Maceration was performed in a water bath and heated for 3–5 h until the splits exhibited a whitish and soft texture. For each sample, 30 undamaged or unbroken fibers were carefully observed under a microscope and measured using the Zen Lite software. Measurements included fiber length, fiber diameter, and lumen diameter, whereas the cell wall thickness was calculated based on the recorded measurements of the fiber and lumen diameters (Figure 3).

Physical Properties

A culm ring 125 mm high was split into two slats, which measured 25 mm × culm wall thickness (CWT) × 125 mm,

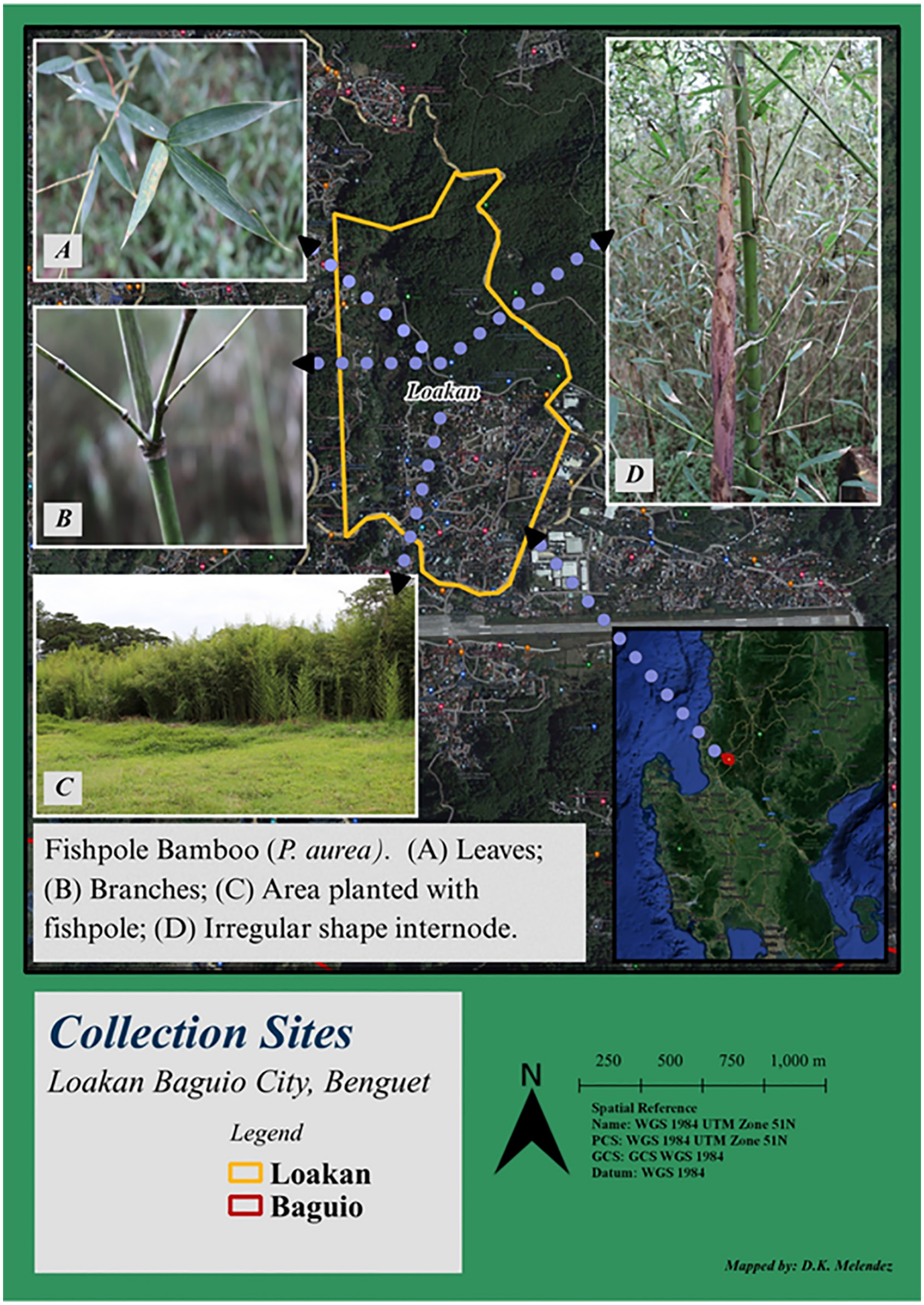

Figure 1. Fishpole bamboo collection site: [A] leaves; [B] branches; [C] area planted with fishpole; [D] irregular shape internode.

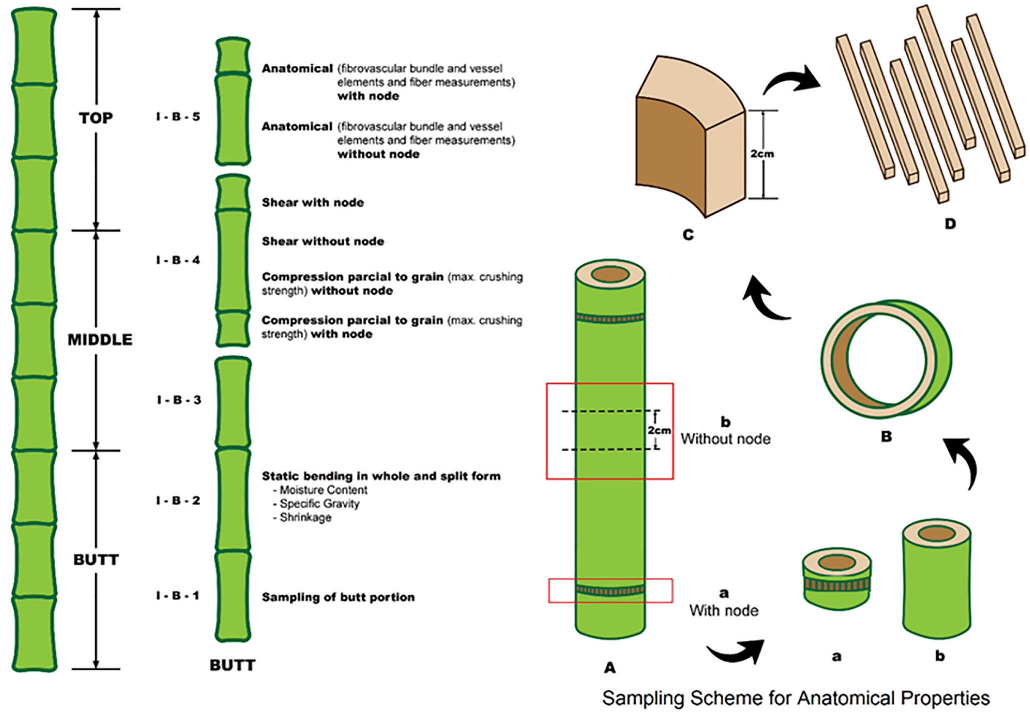

Figure 2. Sampling scheme used in the study.

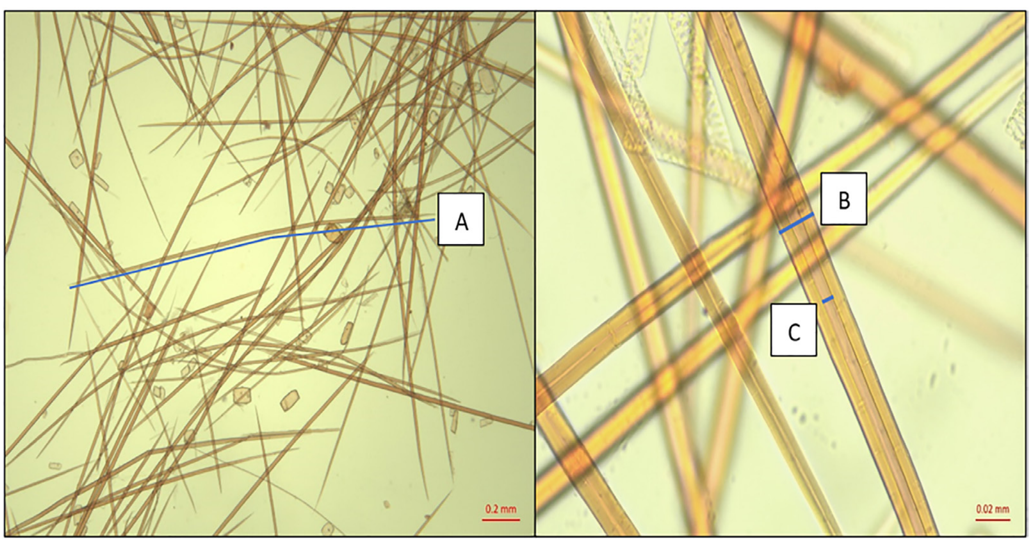

Figure 3. Fiber measurement of fishpole bamboo: [A] fiber length; [B] fiber diameter; (C) lumen diameter.

using a sharp bolo. From each slat, a sample measuring 25 mm × 25 mm × CWT was prepared for moisture content and relative density determination. For the moisture content, the samples were immediately prepared after the collection to retain the green state of the bamboo. Relative density, on the other hand, was determined at oven-dry conditions. The other slat, which measured 25 mm × CWT × 100 mm, was used to determine the shrinkage properties from green to over-dry condition (Figure 4) in accordance with ASTM D143 (2019), with adjustments made to the sample size. A total of 72 samples were used to determine each of the physical properties. The MC and RD were computed using Equations 1 and 2, and shrinkage properties were computed using Equation 3.

$$MC = \left(\frac{W_i - W_o}{W_o}\right) x\, 100 \qquad (1)$$

where: MC = moisture content (%); W_i = initial weight

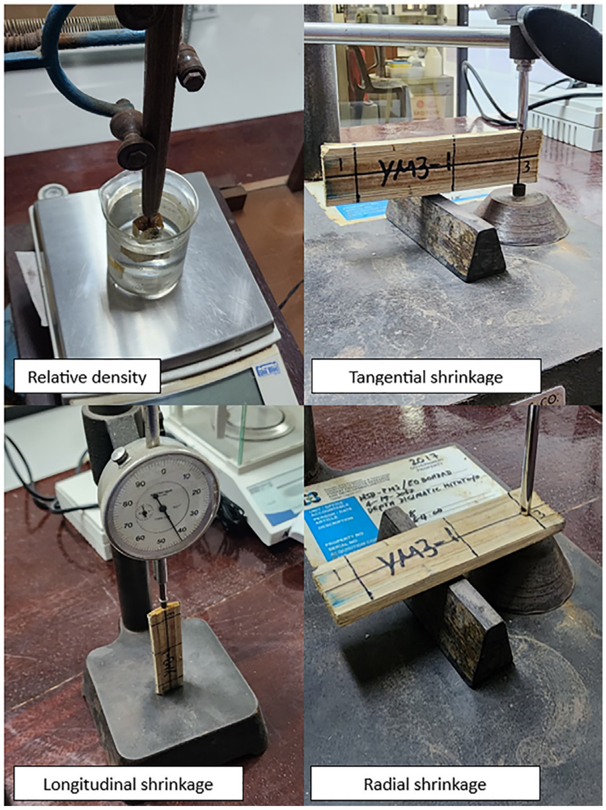

Figure 4. Physical properties determination.

(g); W_o = oven dry weight (g)

$$RD = \frac{W_o}{W_d} \quad (2)$$

where: RD = relative density; W_o = oven dry weight (g); W_d = weight of displaced water (g)

$$S_a(\%) = \frac{D_i - D_o}{D_i} x\, 100 \quad (3)$$

where S_a = shrinkage from green to oven-dry conditions (%), D_i = initial dimension (mm); D_o = oven-dry dimension (mm).

Mechanical Properties

The mechanical properties were tested following ISO 22157:2019. Static bending, maximum compression, and shear strength were investigated at green conditions (Figure 5). A total of 18 samples were used to determine static bending. For the maximum compression and shear strength, two types of samples were prepared – namely, samples with node and without node with a total of 36 samples for each set of properties. The 300 kN Universal Testing Machine was used for all testing. The testing machine operated at a speed of 15 mm/min for static bending, whereas for maximum compression and shear strength tests, the testing speed was set to 0.6 mm/min.

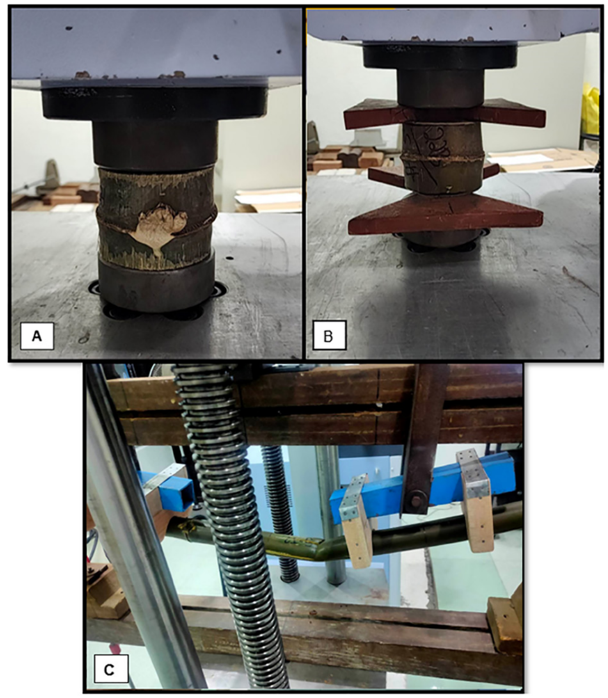

Figure 5. Compression strength (A), shear strength (B), and static bending (C) properties determination of bamboo culms.

Statistical Analysis

The statistical analysis was carried out using R Studio version 4.2.1 (R Core Team 2022). To evaluate the significance of mean differences, one-way analysis of variance (ANOVA) was utilized for assessing the morphological properties, physical properties, and static bending strength. In contrast, two-factor ANOVA was employed to determine the significance of mean differences in anatomical properties, compression strength, and shear strength – namely, height levels and presence or absence of node. In cases where significant differences were detected, Tukey's honestly significant difference test was performed to identify which means were significantly different.

RESULTS

Morphological Properties

The sample exhibited an average culm length of 8.69 m. Among the different portions, the middle displayed the highest average internode length of 25.20 cm, followed by the top (18.20 cm), and the bottom (17.80 cm) (Table 1). The average culm diameter and culm wall thickness

Table 1. Properties of fishpole bamboo at different height levels.

Properties	Height levels			Average	*P*-value
	Bottom	Middle	Top		
Morphological					
Internode length (cm)	17.80b (± 2.14)	25.20a (± 2.37)	18.20b (± 2.63)	20.40	< 0.001*
Culm diameter (mm)	42.50a (± 3.23)	31.30b (± 5.74)	15.30c (± 5.01)	29.70	< 0.001*
Culm wall thickness (mm)	5.48a (± 0.79)	4.17b (± 0.51)	3.29c (± 0.36)	4.31	< 0.001*
Anatomical					
Fiber length (mm)	1.88a (± 0.687)	1.80a (± 0.631)	1.60b (± 0.723)	1.76	< 0.001*
Fiber diameter (um)	19.80a (± 5.04)	18.10b (± 5.21)	17.10c (± 4.35)	18.33	< 0.001*
Lumen diameter (um)	4.63a (± 2.93)	4.15a (± 2.65)	3.55b (± 1.90)	4.11	< 0.001*
Cell wall thickness (um)	7.59a (± 1.96)	6.99a (± 1.95)	6.78b (± 1.78)	7.12	< 0.001*
Physical					
Moisture content (%)	76.20a (± 13.40)	72.90b (± 10.94)	67.00b (± 10.83)	72.03	0.033*
Relative density	0.733b (± 0.076)	0.787b (± 0.083)	0.902a (± 0.295)	0.807	0.008*
Radial shrinkage (%)	5.49b (± 0.59)	6.94a (± 1.61)	6.96a (± 1.27)	6.46	< 0.001*
Tangential shrinkage (%)	3.71a (± 1.13)	2.02b (± 1.04)	0.95c (± 1.18)	2.22	< 0.001*
Longitudinal shrinkage (%)	0.22a (± 0.49)	0.50a (± 0.84))	0.19a (± 0.33)	0.30	0.265^{ns}
Volumetric shrinkage (%)	9.01a (± 1.16)	8.68a (± 1.70)	8.14a (± 1.85)	8.61	0.166^{ns}
Mechanical					
Modulus of rupture (MPa)	58.80b (± 23.54)	54.80b (± 8.16)	95.50a (± 18.09)	69.70	0.004*
Stress at the proportional limit (MPa)	31.50b (± 14.52)	43.10ab (± 6.83)	59.30a (± 13.54)	44.60	0.026*
Modulus of elasticity (GPa)	2.90b (± 0.63)	4.29a (± 2.26)	4.22a (± 0.67)	3.81	0.021*
Compression strength (MPa)	29.90a (± 6.18)	28.90a (± 4.61)	29.40a (± 5.35)	29.40	0.894^{ns}
Shear strength (MPa)	2.99a (± 0.31)	2.96a (± 0.58)	2.54a (± 0.67)	2.83	0.087^{ns}

Note: the value inside the parenthesis is the standard deviation. *p*-value: [*] significant; [ns] not significant. Means with the same letter are not significantly different according to Tukey`s *post hoc* test

were 29.70 and 4.31 mm, respectively. Notably, the bottom portion exhibited the highest values for both culm diameter and culm wall thickness, followed by the middle and top portions. Statistical analysis revealed significant differences in internode length, culm diameter, and culm wall thickness along the height levels ($p < 0.05$).

Anatomical Properties

The samples displayed an average fiber length of 1.76 mm, fiber diameter of 18.33 µm, lumen diameter of 4.11 µm, and cell wall thickness of 7.12 µm (Table 1). The bottom portion displayed the highest values, followed by the middle and top. Height level significantly influenced the anatomical properties of fishpole bamboo. Furthermore, the internode sample had the

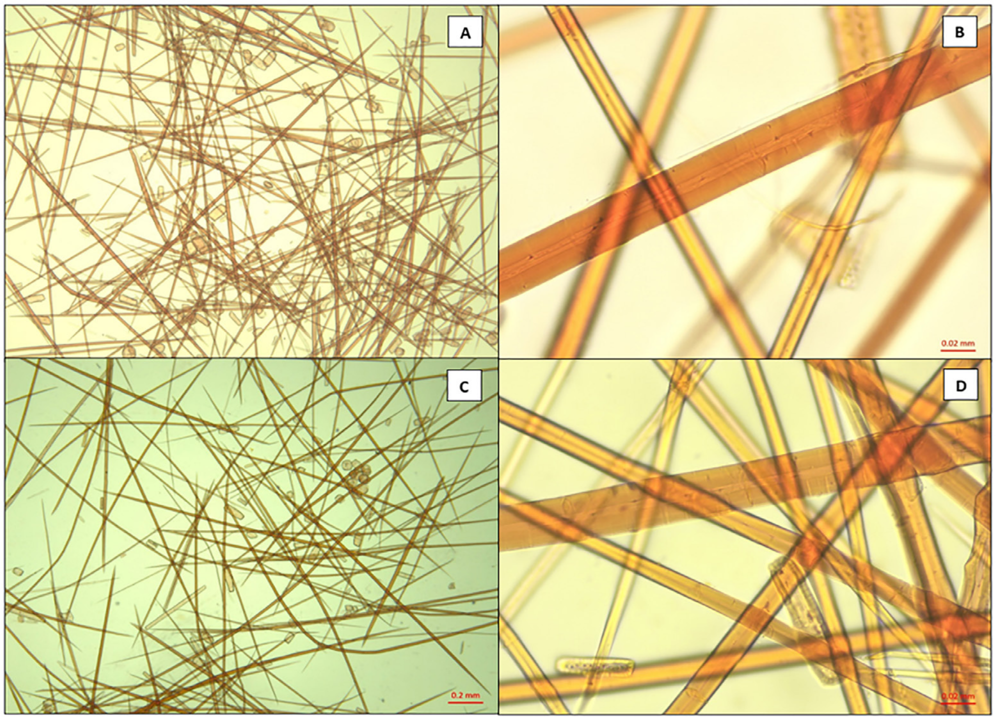

Figure 6. Fibers of fishpole bamboo: nodal section [A] fiber length and [B] fiber and lumen diameter; internode section [C] fiber length and [D] fiber and lumen diameter.

Table 2. Anatomical and mechanical properties of fishpole bamboo at different nodal positions.

Properties	Nodal position		Average	*P*-value
	Nodal	Internode		
Anatomical				
Fiber length (mm)	1.62b (± 0.62)	1.91a (± 0.72)	1.76	< 0.001*
Fiber diameter (um)	18.50a (± 5.32)	18.20a (± 4.65)	18.35	0.279ns
Lumen diameter (um)	4.10a (± 2.67)	4.12a (± 2.46)	4.11	0.895ns
Cell wall thickness (um)	7.22a (± 2.00)	7.03a (± 1.85)	7.12	0.139ns
Mechanical				
Compression strength (MPa)	30.00a (± 6.09)	28.90a (± 4.44)	29.45	0.550
Shear strength (MPa)	2.68a (± 0.54)	2.98a (± 0.56)	2.83	0.103

Note: the value inside the parenthesis is the standard deviation. *p*-value: [*] significant; [ns] not significant. Means with the same letter are not significantly different according to Tukey`s *post hoc* test

highest average fiber length and lumen diameter measuring 1.91 mm and 4.12 µm, respectively (Figure 6). In contrast, node samples exhibited the highest average fiber diameter and cell wall thickness – measuring 18.50 and 7.22 µm, respectively (Table 2). However, only the fiber length was significantly affected by the presence of nodes.

Physical Properties

The fishpole bamboo displayed an average green moisture content of 72.03%, with the bottom portion recording the highest value of 76.20%, followed by the middle portion at 72.90% and the top portion at 67.0% (Table 1). For the oven-dried relative density, the average value was 0.807.

The top displayed the highest RD value of 0.902, followed by the middle with 0.787 and the bottom with 0.733. For shrinkage properties from green to oven dry condition, the average tangential shrinkage was 2.22%, whereas the volumetric shrinkage averaged 8.61%. The bottom portion showed the highest values for both tangential and volumetric shrinkage, followed by the middle and top. Additionally, the average radial shrinkage was 6.46%, with the highest value observed at the top (6.96%), followed by the middle (6.94%) and the bottom (5.49%). Lastly, the average longitudinal shrinkage exhibited a value of 0.30%. Among the portions, the middle recorded the highest value (0.50%), followed by the bottom (0.22%) and the top (0.19%). The statistical analysis showed that the oven-dried relative density, green moisture content, and radial and tangential shrinkage were significantly influenced by the height levels.

Mechanical Properties

The samples exhibited notable characteristics in static bending, modulus of elasticity, modulus of rupture, and stress at the proportional limit (Table 1). The recorded average values for these properties were 3.81 GPa, 69.7 MPa, and 44.6 MPa, respectively. Stress at the proportional limit showed an increasing trend from the bottom to the top portion of the bamboo, whereas the modulus of rupture decreased from the bottom to the middle but increased at the top. Conversely, the highest modulus of elasticity value was observed in the middle (4.29 GPa), followed by the top (4.22 GPa) and the bottom (2.90 GPa). The static bending properties were significantly influenced by height. The compression strength and shear strength of the fishpole bamboo averaged 29.40 and 2.83 MPa, respectively, with the bottom portion exhibiting the highest recorded values for both compression (29.9 MPa) and shear strength (2.99 MPa). Conversely, the middle portion gave the lowest compression strength (28.9 MPa), whereas the top displayed the lowest shear strength (2.54 MPa). There are no significant differences in compression and shear strength along the height of the bamboo.

DISCUSSION

Morphological Properties

The height of the bamboo specimens in this study (8.69 m) corresponds to those of Roxas *et al.* (2012), Elejoste *et al.* (2022), and Seixas *et al.* (2022). It is noteworthy that the collection sites in those studies shared similar conditions with the present study, with elevations above 500 m asl and average temperatures ranging from 18–19 ºC. Like other bamboo such as *Bambusa spinosa, Dendrocalamus asper*, *B. vulgaris*, *Gigantochloa levis*, *D. merrillianus,* and *Schizostachyum lumampao* (Espiloy *et al.* 1992), the internode length of the middle portion of the fishpole bamboo was significantly longer compared to the bottom and top. Roxas *et al.* (2012) noted that the lower internodes of fishpole bamboo are often irregularly shortened and swollen (Figure 1D).

Table 3. Comparison of the properties of fishpole bamboo observed in this study with other economically important bamboo species.

Properties	*Phyllostachys aurea*	*Bambusa spinosa*	*Bambusa vulgaris*	*Gigantochloa levis*	*Dendrocalamus asper*	*Dendrocalamus merrillianus*	*Schizostachyum lumampao*
Morphological							
Internode length (cm)	20.40	31.00	28.60	30.66	42.90	25.27	51.63
Culm diameter (cm)	2.97	7.57	7.80	6.30	11.63	5.37	5.23
Culm wall thickness (mm)	4.31	13.67	10.00	11.67	15.00	18.67	5.00
Anatomical							
Fiber length (mm)	1.76	1.95	2.33	1.80	3.78	2.16	2.42
Fiber diameter (µm)	18.33	18.00	17.00	22.00	19.00	14.00	14.00
Lumen diameter (µm)	4.11	4.00	4.00	6.00	7.00	6.00	6.00
Cell wall thickness (µm)	7.12	7.00	7.00	8.00	6.00	4.00	4.00
Physical							
Moisture content (%)	72.03	92.80	95.50	117.30	119.20	106.20	173.70
Relative density	0.80	0.64	0.64	0.54	0.55	0.60	0.48
Radial shrinkage (%)	6.46	12.00	14.10	11.00	14.70	12.00	18.70
Tangential shrinkage (%)	2.22	8.50	11.90	6.60	7.50	8.10	5.90

Source: Espiloy (1996)

In terms of internode length, fishpole bamboo has a shorter average than most commercial species (Espiloy 1996) (Table 3). However, other features such as tapering and culm wall thickness should also be considered. The present values for culm diameter are consistent with the findings of Roxas *et al.* (2012), Elejoste *et al.* (2022), and Seixas *et al.* (2022). Fishpole bamboo has a smaller diameter than the bamboo species studied by Espiloy (1996).

For culm wall thickness, the specimens gave values similar to the findings of Roxas *et al.* (2012) but slightly higher than the findings of Seixas *et al.* (2022). Moreover, it was lower than the values reported by Espiloy (1996) for commercial bamboo species. However, its culm wall thickness was close to the value of *buho* (*Schizostachyum lumampao*). According to Liese (1998), the decrease in culm wall thickness toward the top portion can be attributed to several factors; the decrease in culm wall thickness toward the top is due to the proximity to the apical growing points of the bamboo and includes the fact that the leaves and branches at the top are prioritized for photosynthesis. Additionally, it can also be related to the cell tissue of the bamboo culm. Toward the top portion, a significant decrease in the proportion of parenchyma cells in the bamboo culm has been observed (Villareal *et al.* 2020).

Anatomical Properties

In terms of fiber length, fishpole bamboo exhibited a relatively lower value compared to the bamboo species examined by Espiloy (1996) (Table 3). From the bottom to the top portion, the fiber length of the fish pole bamboo decreases. These findings are consistent with those reported by Villareal *et al.* (2020), Razak *et al.* (2010), Nordahlia *et al.* (2011), and Huang *et al.* (2015) for various bamboo species. However, Pu and Du (2003) reported longer fiber length in the bottom portion of *Dendrocalamus sinicus*. Different variations found among various bamboo species might have resulted from differences in growth rates among the species (Latif and Tamizi 1992).

Regarding fiber diameter, the fishpole bamboo (18.33 µm) exhibited wider fibers compared to *D. merrillianus*, *S. lumampao*, *B. vulgaris*, and *B. blumeana* (Table 3). Similarly, the fiber diameter decreased toward the top portion, which is similar to the findings of Villareal *et al*. (2020) and Nordahlia *et al.* (2011). On the other hand, the lumen diameter of the fish pole bamboo (4.11 µm) gave a relatively lower value than the commercial bamboo species studied by Espiloy (1996), except for *B. spinosa* and *B. vulgaris* (Table 3).

In terms of cell wall thickness, the fishpole bamboo exhibited thicker cells compared to the bamboo species studied by Espiloy (1996) except for the bolo (*Gigantochloa levis*). Toward the top portion, there was a significant decrease in cell wall thickness. These findings are consistent with results from Villareal *et al.* (2020), Razak *et al.* (2010), Nordahlia *et al.* (2011), and Huang *et al.* (2015) across various bamboo species. However, Mohmod and Mustafa (1992) reported that height levels did not significantly affect the cell wall thickness of *Bambusa spinosa*. They also observed that the decrease in cell wall thickness toward the top portion could possibly be associated with an increase in lumen diameter.

For fiber length, the internode exhibited a significantly higher fiber length (1.91 mm) than the node (1.62 mm). Similar findings were observed on other bamboo species such as *G. brang*, *G. levis*, *G. scortechiini*, and *G. wrayi* (Mustafa *et al.* 2011).

According to Shao *et al.* (2010), the internode of the bamboo culm undergoes elongation and expansion during growth, facilitating the development of longer and more stretched fibers within this region. In contrast, nodes introduce structural complexities owing to the attachment of branches, resulting in variations in the fiber arrangement and shorter fiber length within the section.

Additionally, the nodal section displayed a slightly thicker fiber diameter (18.5 µm) than the internode (18.2 µm). Conversely, it exhibited a slightly thinner lumen diameter (4.10 µm), resulting in a relatively thicker cell wall thickness (7.22 µm) than the internode section's cell wall thickness (7.03 µm). These findings align with previous research conducted by Mustafa *et al.* (2011), Shao *et al.* (2010), and Lybeer (2006), which also reported similar observations. According to Lybeer (2006) and Shao *et al.* (2010), the increased cell wall thickness in the nodes is possibly because of the higher concentration of vascular bundles and the structural complexities present within the node.

Physical Properties

The green moisture content of the fishpole bamboo samples was lower than that of the other bamboo species (Espiloy 1996). This suggests that the fishpole bamboo culm may dry faster than other bamboo species (Cuaresma 2022). A decreasing trend in moisture content towards the top portion was also observed in different bamboo species (Razak *et al.* 2009, 2010; Nordahlia *et al.* 2011; Siam *et al.* 2019; Villareal *et al.* 2020). According to Nordahlia *et al.* (2011), this trend may be attributed to the decreasing percentage of parenchyma cells toward the top portion. These cells contribute to water storage, and the decrease in their abundance results in lower moisture content in the culm (Siam *et al.* 2019). Moreover, Seixas *et al.* (2012) reported that there is a 22.64% decrease in parenchyma cells and a 44.44% increase in vascular bundles of fishpole bamboo from the bottom to the top.

In terms of oven-dried relative density, the value observed in the fishpole bamboo (0.807) was higher compared to commercial bamboo species studied by Espiloy (1996) (Table 3). The results indicate that the mechanical properties of the fishpole bamboo could likely be higher than those of the latter. Toward the top portion, the relative density of the fishpole bamboo significantly increased. This increase in relative density toward the top portion was also observed in other bamboo species (Villareal *et al.* 2020; Razak *et al.* 2009, 2010; Nordahlia *et al.* 2011).

The increase in relative density towards the top portion could probably be attributed to the narrow and more concentrated vascular bundles in that section (Mohmod and Mustafa 1992). Additionally, Correal and Arbalaez (2010) reported that the high amount of sclerenchyma cells at the top portion can also contribute to the higher relative density. According to Seixas *et al.* (2022), the concentration of sclerenchyma cells and vascular bundles in fishpole bamboo increased by 22.22 and 44.44%, respectively, toward the top portion. This structural change resulted in an increase in the relative density of the bamboo.

Based on the relative density classification, the relative density of fishpole bamboo was classified as higher than that of commercial bamboo species in the Philippines (Alipon and Bondad 2008). These findings suggest that fishpole bamboo possesses superior mechanical properties compared to other species. A higher relative density implies denser and more structurally robust bamboo, which indicates its potential for enhanced mechanical performance. This attribute makes fishpole bamboo a promising choice for applications requiring strong and durable bamboo materials, especially in cases where a large diameter is not necessary such as furniture, handicrafts, sporting goods (*e.g.* fishing rods, javelins, ski poles), and tool handles.

Compared to Espiloy's (1996) local commercial bamboo, the fishpole bamboo exhibited lower radial (6.47%) and tangential shrinkage (2.23%) (Table 3). The samples demonstrated a significant increase in radial shrinkage and a significant decrease in tangential shrinkage toward the top portion.

According to Siam *et al.* (2019), the decrease in shrinkage toward the top portion may be due to an increase in the proportion of vascular bundles and a decrease in the proportion of parenchyma cells in that area. Furthermore, the higher percentage of radial shrinkage observed in the bottom portion of the bamboo is attributed to the presence of more parenchyma cells, which contribute to water storage and result in higher moisture content (Razak *et al.* 2012). According to Seixas *et al.* (2022), the parenchyma percentage of the bottom portion of the fishpole bamboo was 29.26% higher compared to the top. Based on the shrinkage classification by Alipon *et al.* (2005), the fishpole bamboo exhibited moderately low volumetric shrinkage (8.61%), which is lower than that of *Guadua angustifolia* (25.49%) (Villareal *et al.* 2020).

Mechanical Properties

The fishpole bamboo exhibited higher strength properties, as indicated by its higher stress at the proportional limit (44.60 MPa) and modulus of rupture (69.70 MPa) compared to local commercial bamboo (Espiloy 1996). However, its modulus of elasticity (3.81 GPa) was relatively lower, except when compared to *D. asper*. The modulus of elasticity measured in this study was notably lower than the value reported by Elejoste *et al.* (2022) for fishpole bamboo (4.09 GPa). These results highlight the potential of fishpole bamboo as a promising alternative raw material to commercial bamboo for applications that need strength and small-diameter culms.

The samples in the current study exhibited significant variations in their mechanical properties along the culm length, with the top portion demonstrating higher static bending properties (Figure 7). The trend of mechanical strength along the culm was consistent with the results obtained in other bamboo species (Espiloy 1996, Nordahlia *et al.* 2011; Bondad *et al.* 2023). Unfortunately, this portion is often unsuitable for use due to its small diameter. The bottom and middle portions, however, remain viable for various applications. Interestingly, when compared to the bottom and middle culms of commercial species (Espiloy 1996), the bottom and middle of the fishpole bamboo exhibited higher strength values, making them promising alternative materials for small-diameter applications (Table 1).

The high static bending properties in the top culm may be attributed to its higher relative density resulting from the higher concentration of vascular bundles and sclerenchyma cells (Nordahlia *et al.* 2011). According to Malanit *et al.* (2008), the static bending properties of bamboo are significantly correlated with relative density. As mentioned earlier, the top portion of fishpole bamboo exhibited a higher percentage of vascular bundles and sclerenchyma cells. A similar observation was also observed in other erect bamboo (Espiloy 1996; Siam *et al.* 2019) and climbing bamboo species (Bondad *et al.* 2023).

The fishpole bamboo exhibited relatively lower compression strength (29.4 MPa) than other commercial bamboo species (Espiloy 1996). The bottom and top portions had the highest compression strength values, whereas the middle had the lowest. The high compression strength observed in the bottom and the top of the fishpole

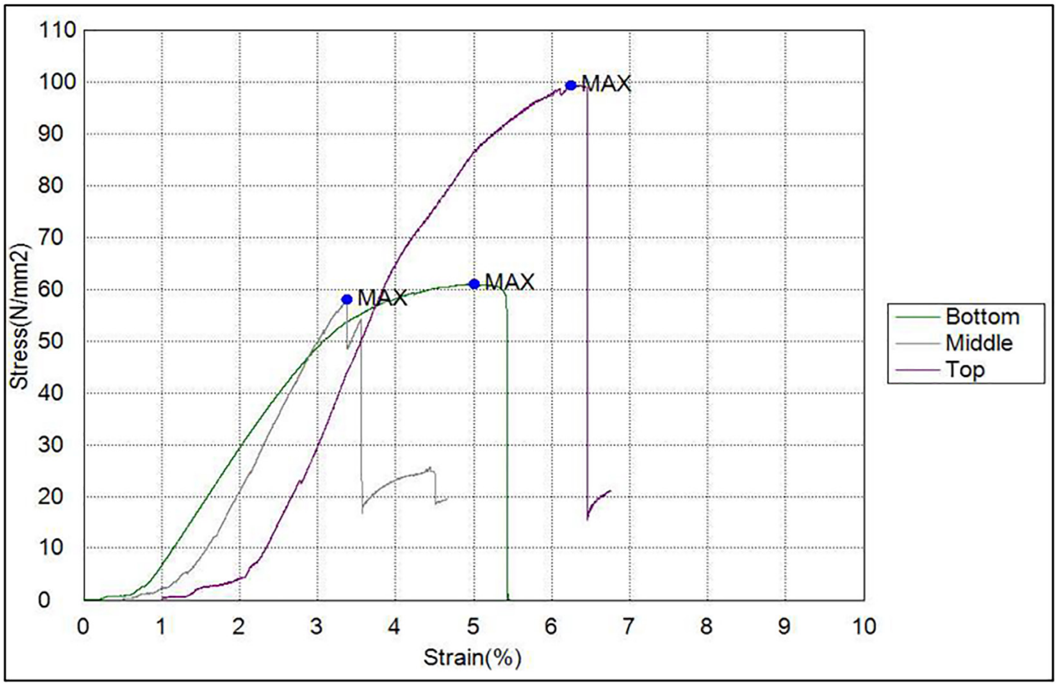

Figure 7. Stress-strain graph of fishpole bamboo.

bamboo can be attributed to its high RD. This trend aligns with the findings of Bondad *et al.* (2023) for *Cyrtochloa major*, *Dinochloa dielsiana*, and *C. luzonica*, as well as Espiloy and Espiloy (1992) for *B. vulgaris*. Bondad *et al.* (2023) noted a positive relationship between relative density and compression strength in bamboo, which is consistent with the observations of the present study. However, morphological properties such as culm diameter and culm wall thickness can also influence the compression strength of the bamboo (Liu *et al.* 2021; Omaliko and Ubani 2021).

Kenneth and Uzodimma (2021) and Chaowana *et al.* (2015) also reported a positive correlation between relative density and compression strength in different types of erect bamboo. This correlation can be attributed to variations in the distribution of vascular bundles, chemical composition, and cell structure across the height and position of the bamboo culm. These factors influence the mechanical properties of bamboo and contribute to its compression strength (Kenneth and Uzodimma 2021). For instance, bamboo with a higher concentration of vascular bundles and sclerenchyma cells could have a higher relative density, resulting in higher strength. Additionally, bamboo with higher holocellulose and α-cellulose could likely have a higher relative density, leading to higher strength (Hartono *et al.* 2022).

The shear strength of the fishpole bamboo (2.83 MPa) was found to be lower than the bamboo species examined by Bautista *et al.* (2021). In general, shear strength decreased as height increased. These findings support the results reported for *Cephalostachyum mindorense* and *C. luzonica* (Bondad *et al.* 2023).

The presence of nodes in the fishpole bamboo culm resulted in a 3.80% increase in compression strength. This increase in strength can be attributed to several factors – including shorter fiber length, higher lignin content, and higher concentration of truncated vascular bundles in the nodal region (Bondad *et al.* 2023). Similar findings of enhanced strength properties in bamboo with nodes have been observed in *Gigantochloa scortechinii* (Hamdan *et al.* 2009) and *Phyllostachys edulis* (Liu *et al.* 2021).

For shear strength, the internode exhibited 11.19% higher strength than the nodal section. This finding is similar to the observations of Bautista *et al.* (2021), Salzer *et al.* (2018), and Oka *et al.* (2014), who also reported higher shear strength in the internode section of *G. apus*, *B. philippinensis*, *B. vulgaris*, *B. blumeana*, and *G. atroviolaceae*.

Potential Uses of Fishpole Bamboo

The fishpole bamboo is commonly used as a garden ornamental and hedge plant in the Philippines and is planted along roadsides, parks, and forest areas in Baguio City. However, the findings of the present study indicate that the culms of fishpole bamboo offer potential applications beyond their ornamental value. For instance, it has a high relative density, dimensional stability, faster drying time, and higher static bending properties than other commercial bamboo species. Compression and shear strength, however, are lower.

Despite its inferior morphological properties compared to commercial species, fishpole bamboo has RD and mechanical properties that are suitable for applications such as furniture, window frames, and handicrafts. The unique shape of its internode lends itself well to decorative uses like walking sticks, umbrellas and fan handles, and end-piece support for hammocks, as well as souvenir materials. In Brazil, this bamboo is commonly utilized in the production of rustic bare handicraft furniture (Rusch *et al.* 2019). Likewise, the straight upper culm can be used for fishing rods, ski poles, pulp and paper, musical instruments, utensils, charcoal, javelins, ceiling covers, and in furniture and construction projects, wherein a large diameter is not required. Culms with a diameter exceeding 5.0 cm are suitable for laminated or engineered bamboo (Natividad and Jimenez 2015; Rusch *et al.* 2019). Moreover, the species can be processed into pellets and briquettes (Brand *et al.* 2019; Chaves *et al.* 2021).

CONCLUSION

The study provides valuable benchmark information for the bamboo industry regarding fishpole bamboo properties. Results reveal significant variations in the morphological, anatomical, and physico-mechanical properties along the height of the bamboo culm. Morphological properties like culm diameter and wall thickness decreased significantly toward the top, whereas internode length increased. Anatomical properties also decreased toward the top, whereas fiber length was significantly higher in the internodes than in the nodes. Meanwhile, moisture content, tangential shrinkage, and volumetric shrinkage decreased toward the top, whereas relative density and radial shrinkage increased. Static bending properties such as MOR, MOE, and SPL also significantly increased. Along with the height levels, compression, and shear strength show different trends, and no significant differences between nodal and internode portions were observed.

Based on these findings, fishpole bamboo is recommended as a possible source of raw materials for various products – including furniture, window frames, handicrafts, cane or walking sticks, stair balusters, umbrellas, fan handles, hammock end-piece supports, and souvenirs. It is also suitable for fishing rods, ski poles, pulp and paper, musical instruments, utensils, charcoal, javelins, ceiling covers, and construction projects, wherein a large diameter is unnecessary. Culms with a diameter greater than 5.0 cm are suitable for engineered bamboo, and the bamboo can also be used as a potential raw material source for pellets and briquettes.

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