

Research Paper

CHARACTERIZATION AND POTENTIAL UTILIZATION OF STRING BAMBOO (*Gigantochloa apus*)

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ARTICLE HIGHLIGHTS

- *Gigantochloa apus* shows strong potential for structural and engineered uses.
- Axial and nodal variations significantly affect bamboo fiber anatomy.
- Relative density and strength make *G. apus* suitable for construction and furniture.
- Derived fiber ratios indicate limited papermaking suitability.
- *G. apus* offers broad utilization potential for sustainable industries

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INTRODUCTION

String bamboo (*Gigantochloa apus* [Schult.f.] Kurz ex Munro) is a clumping species native to South and Southeast Asia, with introductions in Brazil, Puerto Rico, and the Philippines (Roxas 2012). It grows up to 16.0 m tall, with culm diameters of 5.0 – 7.0 cm and internodes of 4.0 – 8.0 cm. In the Philippines, it is mainly used for handicrafts and furniture (DENR – ERDB 2016), while in Indonesia, known as Tali or Apus bamboo, it is widely used in construction (Iswanto 2017). In Peru, it is recommended for rural construction, veneers, handicrafts, pulp and paper, textiles, and interior panels (Portal-Cahuana *et al.* 2023). Its flexibility makes it ideal for rope production and curved structures, while its thin culm walls suit lightweight applications like fences and roofs (Larsen 2023).

ABSTRACT

This study assessed the morphological, anatomical, derived ratio, and physico-mechanical properties of string bamboo (*Gigantochloa apus* [Schult.f.] Kurz ex Munro) grown in Baguio City, Philippines, to establish comprehensive property data and explore potential applications. Six mature culms were sampled and tested for its properties following the IAWA, ISO, and ASTM standards. Results revealed that culm diameter and wall thickness decreased significantly by 37.30% and 46.60%, respectively, toward the top portion. Anatomical analysis showed significant decreases in fiber length, fiber diameter, lumen diameter, and cell wall thickness by 15.33%, 13.86%, 24.05%, and 8.43%, respectively, from bottom to top. All derived ratios varied significantly between the node and internode portions. The node portion exhibited higher values for cell wall fraction, Runkel ratio, Muhlsteph ratio, rigidity coefficient, and Luce's shape factor. Radial and volumetric shrinkage decreased by 29.47% and 31.01%, respectively, toward the top, while shear strength dropped by 47.20%. In contrast, basic relative density, modulus of rupture, modulus of elasticity, and compression strength showed no significant variation along the culm. These findings highlight that *G. apus* is suitable for diverse applications including furniture, handicrafts, construction, engineered bamboo, and biomass products.

Keywords: anatomical properties, *Gigantochloa apus*, mechanical properties, physical properties, string bamboo

The limited use of *G. apus* in the Philippines stems from a lack of property data. Bautista *et al.* (2021) reported a culm diameter of 95.06 mm, wall thickness of 7.98 mm, shear strength of 10.77 MPa, and basic relative density of 0.679. In Indonesia, it has a culm diameter of 4.0 – 8.0 cm, fiber length of 2.35 mm, vascular bundle frequency of 10.5 per mm² (Iswanto 2017), basic relative density of 0.82 – 0.83, moisture content of 83.18 – 102.78%, and tangential-to-radial shrinkage of 0.58 – 0.84 (Maulana *et al.* 2021). In Peru, its moisture content is 30.30 – 129.88%, with basic relative density of 0.49 – 0.85, and volumetric shrinkage of 12.44 – 28.83% (Portal-Cahuana *et al.* 2023).

Characterizing bamboo properties is key to optimizing its use in construction, composites, pulp, and furniture. Morphology, anatomy,

density, and moisture content directly influence suitability - larger culms suit construction, smaller ones fit furniture, and longer fibers enhance pulp and composites. Bautista *et al.* (2021) highlighted the need for further studies on *G. apus*, particularly its axial variation. Therefore, this study aimed at providing a comprehensive characterization of *G. apus* in the Philippines, integrating morphological, anatomical, derived ratio, physical, and mechanical properties. Our study specifically examined axial variation along the culm and differences between nodes and internodes, which had not been systematically reported. The objective was to generate a comprehensive data to broaden the applications of *G. apus* and provide scientifically grounded options for farmers, manufacturers, and the bamboo industry.

MATERIALS AND METHODS

Sample Preparation

Six mature *G. apus* culms (4 – 5 years old) were collected from different clumps in Loakan, Baguio City (16.3877° N; 120.6137° E, 1,570 m elevation) (Fig. 1). Harvested 30 cm above the ground, they were divided into bottom, middle, and top sections. Anatomical analysis used 20-mm samples from nodes and internodes, while 125-mm samples from bending test specimens assessed moisture content, relative density, and shrinkage.

Compression and shear tests included samples with and without nodes (Fig. 2).

Determination of Morphological Properties

The diameter of the bamboo was calculated as the average of two perpendicular measurements taken across opposing points on the outer surface of the culm. To determine the culm wall thickness, four measurements were taken at 90° intervals around the circumference using a vernier caliper, following the ISO 22157:2019 standard.

Determination of Fiber Morphology

Fiber dimensions were evaluated following the procedure of Espiloy *et al.* (1999). Bamboo samples were prepared into matchstick-sized and subjected to maceration in a solution of equal parts (50%) acetic acid and hydrogen peroxide. The samples were heated in a water bath for 3 – 5 hours until softened and whitish, which facilitated the separation of individual fibers. After rinsing with distilled water to remove residual chemicals, 30 intact fibers per section and portions were mounted on glass slides and examined under a Zeiss Primo Star microscope. Fiber properties were measured using Zen Lite software. Cell wall thickness was determined as the difference between fiber diameter and lumen diameter. All measurements followed the standards of the International Association of Wood Anatomists (IAWA) (Wheeler *et al.* 1989).



Figure 1 Gigantochloa apus

Notes: A = culm; B = branch; C = culm sheaths; and D = leaves.

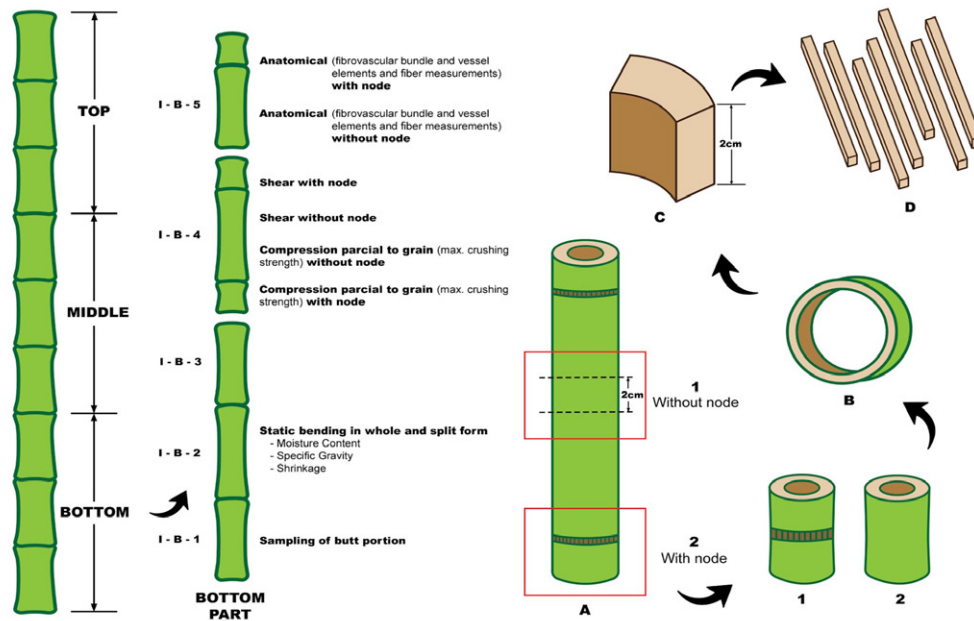


Figure 2 Sampling scheme used to determine the properties of the *G. apus*

Determination of Derived Ratios

Derived values such as the Runkel ratio (RR), slenderness ratio (SR), flexibility ratio (FR), Mulhsteph ratio (MR), rigidity coefficient (RC),

and Luce’s shape factor (LSF) were calculated using the fiber morphology data. The formulas used for these calculations and their relevance to pulp and paper properties are presented in Table 1.

Table 1 Derived ratios, their corresponding formulas, and their impact on pulp and paper properties

Derived ratio	Related to pulp and paper properties	Formula
Cell wall fraction	Bending resistance (negatively)	$(2 \times \text{CWT})/\text{FD} \times 100$
Runkel ratio	Pulp yield (positively) and digestibility (negative)	$(2 \times \text{CWT})/\text{LD}$
Flexibility ratio	Tearing and tensile strength (positive)	$\text{LD}/\text{FD} \times 100$
Slenderness ratio	Tensile strength (positive)	FL/FD
Mulhsteph ratio	Flexibility and tensile (positive)	$(\text{FD}2 - \text{LD}2)/\text{FD}2 \times 100$
Rigidity coefficient	Bending and tensile strength (positive)	CWT/FD
Luce’s shape factor	Resistance to beating (positively)	$(\text{FD}2 - \text{LD}2) / \text{FD}2 + \text{LD}2)$

Notes: CWT = cell wall thickness; FD = fiber diameter; LD = lumen diameter; FL = fiber length.

Determination of Physical Properties

A 125-mm-high culm ring was split into two slats (25 mm × CWT × 125 mm). From each slat, a 25 mm × 25 mm × CWT sample was prepared for green moisture content (MC) and basic relative density (RDb), with MC measured immediately and RDb determined under oven-dry conditions. The remaining slat (25 mm × CWT × 100 mm) was used for shrinkage tests from green to oven-dry state, following ASTM D143 (2019). A total of 72 samples were tested for each physical property, calculated using Equations 1 – 3 as follows.

$$MC (\%) = (W_i - W_o) / W_o \times 100$$

where:

MC = Green moisture content (%)

W_i = Initial weight (g)

W_o = Oven dry weight (g)

$$RD_b = W_o / W_d$$

where:

RDb = Basic relative density

W_o = Oven dry weight (g)

W_d = Volume (g)

$$S_a (\%) = (D_i - D_o) / D_i \times 100$$

where:

S_a = Shrinkage from green to oven-dry conditions (%)

D_i = Initial dimension (mm)

D_o = Oven-dry dimension (mm)

Determination of Mechanical Properties

Mechanical properties were tested under green conditions following ISO 22157:2019. The specimen size was determined according to the standard: static bending specimens had a length of 30 × culm outer diameter, while compression and shear specimens tested parallel to the grain had a length of 10 × culm wall thickness. A total of 18 specimens were tested for static bending, and 36 specimens each for compression and shear strength parallel to the grain. For compression and shear, half of the specimens were prepared with nodes and without node. All tests were conducted using a 300 kN Universal Testing Machine, with a loading speed of 15 mm/min for bending and 0.6 mm/min for compression and shear.

Statistical Analysis

Statistical analysis was conducted using Jamovi version 2.3 (The Jamovi Project 2023). Data normality was verified using the Kolmogorov–Smirnov test. One-way analysis of variance

(ANOVA) was employed to assess mean differences in morphological properties, physical properties, and static bending strength across height levels. Two-way ANOVA was applied to evaluate anatomical properties, derived ratios, compression and shear strength parallel to the grain, with height level (bottom, middle, top) and node presence (with or without nodes) as factors. When significant differences were detected, Tukey's honestly significant difference (HSD) test was used for post hoc comparisons.

RESULTS AND DISCUSSION

Morphological Properties

G. apus culms measured 14.69 – 17.30 m tall, with a mean diameter of 66.51 mm and wall thickness of 6.48 mm. Diameter and thickness decreased significantly from bottom (75.06 mm, 8.54 mm) to top (51.46 mm, 4.56 mm) ($P < 0.05$) (Table 2).

The height of *G. apus* in this study exceeded previous reports (Hartono *et al.* 2022a; Maulana *et al.* 2021), which may be attributed to environmental factors such as soil conditions, temperature, elevation, and relative humidity (Parlucha *et al.* 2022). The present sampling site is classified as Climatic Type I, situated at 1,570 m above sea level, with an average temperature of 19.3 °C, relative humidity of 87%, annual rainfall of 3,463 mm, and clay-type soil. Diameter fell within the 40 – 80 mm range (Hartono *et al.* 2022a) but was smaller than values from Maulana *et al.* (2021) and Bautista *et al.* (2021). The 31.44% diameter and 46.60% thickness reduction align with bamboo's apical growth and parenchyma cell decline. Compared to commercial species (Espiloy 1996), *G. apus* had thinner walls, similar to *Schizostachyum lumampao* (Table 3).

Fiber Morphology

G. apus fibers averaged 2.61 mm in length, with fiber and lumen diameters of 23.41 μm and 7.79 μm, and a cell wall thickness of 7.81 μm (Table 2). Internode fibers (2.82 mm) were longer than node fibers (2.40 mm), with fiber length decreasing 15.33% from bottom (2.87 mm) to top (2.43 mm) (Table 4). Fiber diameter was wider at nodes (24.81 μm) than internodes (22.01 μm) and decreased 13.86% along the culm. Lumen diameter was larger in internodes (8.17 μm) than nodes (7.41 μm), decreasing 24.05% toward the top. Nodes had thicker walls (8.70 μm) than internodes (6.92 μm), with an 8.43% reduction along the culm.

Table 2 Culm properties of *G. apus* along the height levels

Properties	Height levels			Average	P value	ITAC Classification
	Bottom	Middle	Top			
<i>Morphological</i>						
Culm diameter (mm)	75.06a (± 4.88)	73.02b (± 6.60)	51.46c (± 5.32)	66.51 (± 6.48)	< 0.000*	-
Culm wall thickness (mm)	8.54 (± 1.49)	6.36 (± 1.10)	4.56 (± 0.55)	6.48 (± 1.98)	< 0.000*	-
<i>Anatomical</i>						
Fiber length (mm)	2.87 (± 8.56)	2.54 (± 8.01)	2.43 (± 7.75)	2.61 (± 8.31)	< 0.001*	I
Fiber diameter (µm)	25.63 (± 6.33)	22.53 (± 5.76)	22.07 (± 6.82)	23.41 (± 6.51)	< 0.001*	-
Lumen diameter (µm)	9.03 (± 6.55)	7.49 (± 5.10)	6.86 (± 4.91)	7.79 (± 5.63)	< 0.001*	-
Cell wall thickness (µm)	8.30 (± 2.17)	7.52 (± 2.48)	7.61 (± 2.96)	7.81 (± 2.58)	< 0.001*	-
<i>Derived ratio</i>						
Cell wall fraction (%)	67.30 ^a (± 17.11)	68.06 ^a (± 17.10)	69.79 ^a (± 16.50)	68.38 (± 16.91)	0.230 ^{ns}	-
Runkel ratio (%)	3.03 ^a (± 2.27)	3.07 ^a (± 2.10)	3.45 ^a (± 2.68)	3.18 (± 2.34)	0.080 ^{ns}	III
Flexibility ratio (%)	32.70 ^a (± 17.11)	31.94 ^a (± 17.10)	30.21 ^a (± 16.50)	31.62 (± 16.91)	0.230 ^{ns}	III
Slenderness ratio (%)	115.75 ^a (± 36.27)	115.08 ^a (± 31.85)	116.02 ^a (± 39.53)	115.62 (± 35.98)	0.940 ^{ns}	-
Mulhsteph ratio (%)	86.39 ^a (± 13.80)	86.88 ^a (± 13.92)	88.16 ^a (± 12.99)	87.15 (± 13.58)	0.310 ^{ns}	III
Rigidity coefficient	1.51 ^a (± 1.13)	1.54 ^a (± 1.01)	1.73 ^a (± 1.34)	1.59 (± 1.17)	0.080 ^{ns}	III
Luce's shape factor (%)	0.78 ^a (± 0.19)	0.79 ^a (± 0.19)	0.81 ^a (± 0.18)	0.79 (± 0.19)	0.270 ^{ns}	-
<i>Physical</i>						
Green moisture content (%)	130.00 ^a (± 20.92)	114.97 ^a (± 45.72)	113.08 ^a (± 38.22)	119.35 (± 34.66)	0.730 ^{ns}	-
Basic relative density	0.51 ^a (± 0.05)	0.57 ^a (± 0.12)	0.57 ^a (± 0.10)	0.55 (± 0.09)	0.547 ^{ns}	-
Radial shrinkage (%)	9.37 ^a (± 2.29)	7.50 ^a (± 2.14)	6.58 ^a (± 1.84)	7.81 (± 2.28)	0.143 ^{ns}	-
Tangential shrinkage (%)	7.59 ^a (± 0.61)	7.48 ^a (± 1.94)	5.64 ^b (± 0.62)	6.90 (± 1.47)	0.048 ^{ns}	-
Longitudinal shrinkage (%)	0.02 ^a (± 0.00)	0.03 ^a (± 0.00)	0.02 ^a (± 0.01)	0.02 (± 0.00)	0.863 ^{ns}	-
Volumetric shrinkage (%)	2.53 ^b (± 2.53)	3.14 ^a (± 3.14)	1.41 ^c (± 1.41)	14.11 (± 2.94)	0.049*	-
<i>Mechanical</i>						
Modulus of rupture (MPa)	59.81 ^a (± 19.22)	52.89 ^a (± 17.31)	60.61 ^a (± 23.55)	57.77 (± 17.33)	0.723 ^{ns}	-
Modulus of elasticity (GPa)	13.74 ^a (± 4.08)	13.68 ^a (± 2.02)	14.52 ^a (± 4.52)	13.98 (± 3.50)	0.910 ^{ns}	-
Stress at the proportional limit (MPa)	25.79 ^a (± 9.66)	27.50 ^a (± 9.06)	41.05 ^a (± 16.08)	31.45 (± 13.30)	0.086 ^{ns}	-
Compression strength parallel to the grain (MPa)	32.79 ^a (± 4.77)	32.39 ^a (± 6.01)	34.84 ^a (± 10.09)	33.34 (± 13.70)	0.706 ^{ns}	-
Shear strength parallel to the grain (MPa)	17.15 ^a (± 3.90)	13.36 ^{ab} (± 4.50)	10.60 ^b (± 3.40)	7.19 (± 4.71)	0.002*	-

Notes: * = a significant difference at the 0.05 level of confidence; ns = non-significance; means for height levels with different superscripts within a row are significantly different (P < 0.05); ITAC = Indonesian Timber Assessment Criteria for Raw Materials for Pulp and Paper (Hartono *et al.* 2022b).

Fiber length exceeded Maulana *et al.* (2021) and most species in Espiloy (1996) but was shorter than *Dendrocalamus asper* (3.78 mm) (Table 3). Classified as “very long fiber” (Class I) under ITAC (Hartono *et al.* 2022b), *G. apus* is suitable for pulp, composites, and particle board (Iswanto 2017). Fiber length decreased 15.29% from bottom to top, similar to other species, while internode fibers were 14.70% longer due to growth elongation (Shao *et al.* 2010). Fiber and lumen diameters, larger than the diameters in other commercial

bamboo, decreased 13.89% and 17.05%, toward the top respectively (Table 3). Only fiber diameter differed by portion, being 12.72% greater at nodes due to higher vascular bundle concentration (Shao *et al.* 2010).

G. apus cell walls (7.81 μm) were thicker than that of most commercial species except *Gigantochloa levis* (8.00 μm) (Table 3), decreasing 8.34% toward the top. Node walls were 25.72% thicker than internodes, consistent with denser vascular bundles (Shao *et al.* 2010).

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

Properties	<i>Gigantochloa apus</i>	<i>Bambusa spinosa</i> ^a	<i>Bambusa vulgaris</i> ^a	<i>Gigantochloa levis</i> ^a	<i>Dendrocalamus asper</i> ^a	<i>Dendrocalamus merrillianus</i> ^a	<i>Schizostachyum lumampao</i> ^a
<i>Morphological</i>							
Culm diameter (mm)	66.50	75.70	78.00	63.00	116.30	53.70	52.30
Culm wall thickness (mm)	6.48	13.67	10.00	11.67	15.00	18.67	5.00
<i>Fiber morphology</i>							
Fiber length (mm)	2.61	1.95	2.33	1.80	3.78	2.16	2.42
Fiber diameter (μm)	23.41	18.00	17.00	22.00	19.00	14.00	14.00
Lumen diameter (μm)	7.79	4.00	4.00	6.00	7.00	6.00	6.00
Cell wall thickness (μm)	7.81	7.00	7.00	8.00	6.00	4.00	4.00
<i>Physical</i>							
Green moisture content (%)	119.35	92.80	95.50	117.30	119.20	106.20	173.70
Basic relative density	0.55	0.64	0.64	0.54	0.55	0.60	0.48
Radial shrinkage (%)	7.81	12.00	14.10	11.00	14.70	12.00	18.70
Tangential shrinkage (%)	6.90	8.50	11.90	6.60	7.50	8.10	5.90

Note: a = data sourced from Espiloy (1996).

Table 4 Anatomical and mechanical properties of *G. apus* at different portions

Properties	Portion		P value
	Node	Internode	
<i>Anatomical</i>			
Fiber length (mm)	2.40 ^b (± 0.75)	2.82 ^a (± 0.82)	< 0.000*
Fiber diameter (µm)	24.81 ^a (± 6.62)	22.01 ^b (± 6.08)	< 0.000*
Lumen diameter (µm)	7.41 ^a (± 5.37)	8.17 ^a (± 5.87)	0.060ns
Cell wall thickness (µm)	8.70 ^a (± 2.71)	6.92 ^b (± 2.08)	< 0.000*
<i>Derived ratio</i>			
Cell wall fraction (%)	71.42 ^a (± 15.23)	65.34 ^b (± 17.96)	< 0.000*
Runkel ratio (%)	3.55 ^a (± 2.46)	2.82 ^b (± 2.15)	< 0.000*
Flexibility ratio (%)	28.58 ^b (± 15.23)	34.66 ^a (± 17.96)	< 0.000*
Slenderness ratio (%)	99.71 ^b (± 28.50)	131.54 ^a (± 35.66)	< 0.000*
Muhlsteph ratio (%)	89.52 ^a (± 11.62)	84.77 ^b (± 14.93)	< 0.000*
Rigidity coefficient	1.77 ^a (± 1.23)	1.41 ^b (± 1.08)	< 0.000*
Luce shape factor (%)	0.83 ^a (± 0.16)	0.76 ^b (± 0.20)	< 0.000*
<i>Mechanical</i>			
Compression strength parallel to the grain (MPa)	33.41 ^a (± 7.61)	33.27 ^a (± 6.96)	0.956ns
Shear strength parallel to the grain (MPa)	14.59 ^a (± 5.03)	12.82 ^a (± 4.32)	0.199ns

Notes: * = a significant difference at the 0.05 level of confidence; ns = non-significance; means for portion with different superscripts within a row are significantly different (P < 0.05).

Derived Ratio

The derived ratios of *G. apus*, including cell wall fraction (CWF), Runkel ratio (RR), flexibility ratio (FR), slenderness ratio (SR), Muhlsteph ratio (MR), rigidity coefficient (RC), and Luce's shape factor (LSF), are shown in Tables 2 and 4. Across height levels, no significant variation was observed in any of the derived ratios (Table 2), indicating relative stability along the culm. In contrast, significant differences were found between node and internode portions (Table 4), i.e., nodes exhibited higher CWF (8.89%), RR (22.99%), MR (5.44%), RC (23.34%), and LSF (8.80%), whereas internodes had higher FR (19.20%) and SR (36.74%).

The mean CWF of *G. apus* (68.38%) was higher than that of *S. lumampao* (57.14%) and *D. asper* (63.15%) but was lower than that of *Bambusa*

vulgaris (82.35%) and *Bambusa spinosa* (105.88%) (Espiloy 1996). Higher CWF is associated with slower drying due to reduced lumen space (Eloy *et al.* 2024), suggesting that *G. apus* dries faster than *B. vulgaris* but remains above the < 40% ideal threshold for pulp and paper applications.

The RR (3.18%) showed no significant variation along the culm but was 20.56% higher in nodes (3.55%) compared to internodes (2.82%). Its value places *G. apus* in ITAC Class III (Hartono *et al.* 2022b), indicating reduced pulp processability relative to species with RR < 1. This aligns with previous findings that higher RR requires more intensive chemical pulping (Rusch *et al.* 2019). The FR (31.62%) was greater than *B. vulgaris* (23%) but lower than *S. lumampao* (43%) (DOST FPRDI 2007), also falling in Class III in ITAC classification and suggesting limited fiber elasticity for paper applications (Hartono *et al.* 2022b).

The SR (115.62%) exceeded the < 33 ideal, placing it in ITAC Class I and indicating strong, slender fibers suitable for composites and reinforcement panels (Rusch *et al.* 2019; Hartono *et al.* 2022b). Conversely, the MR (87.14%) and RC (1.59%) placed *G. apus* in ITAC Class III, highlighting reduced suitability for pulp production (Hartono *et al.* 2022b). The LSF (0.79) was above the favorable value of < 0.5 (Nagarajaganesh *et al.* 2023), reinforcing its limited papermaking potential but pointing to applications in engineered bamboo and composites.

Physical Properties

G. apus had an average basic relative density (RDb) of 0.55, increasing from 0.51 (bottom) to 0.57 (top). Its green moisture content (MC) averaged 119.34%, decreasing from 130.00% at the bottom to 113.08% at the top. Shrinkage from green to oven-dry averaged 7.81% for radial (RS), 6.90% for tangential (TS), 0.02% for longitudinal (LS), and 14.11% for volumetric (VS), with RS and VS decreasing significantly toward the top ($P < 0.05$) (Table 2).

The MC of *G. apus* (119.35%) was lower than that reported by Portal-Cahuana *et al.* (2023) (155.65%) but higher than that reported by Hartono *et al.* (2022a) (92.08%). It declined along the culm due to reduced parenchyma cells (Nordahlia *et al.* 2011), consistent with a 37.25% increase in parenchyma proportion from bottom to top (Maulana *et al.* 2021).

The RDb (0.55) was lower than that reported by Hartono *et al.* (2022a) (0.82) and Portal-Cahuana *et al.* (2023) (0.60) but higher than that of *G. levis* and *S. lumampao* (Espiloy 1996) (Table 3). Its slight increase with height was attributed to denser vascular bundles and higher fiber content, which increased by 64.29% and 5.0%, respectively, toward the top (Maulana *et al.* 2021). Classified as high-density (Alipon & Bondad 2008), *G. apus* is suitable for furniture, construction, handicrafts, panels, tool handles, and engineered bamboo applications.

The T/R ratio (1.13) exceeded Hartono *et al.* (2022a) (0.72). TS (6.90%) and RS (7.81%) were lower than that of most commercial bamboos (Table 3). VS (14.11%) was lower than that reported by Portal-Cahuana *et al.* (2023) (24.14%) and decreased significantly (30.70%) along the culm due to higher vascular bundle proportion and reduced parenchyma (Maulana *et al.* 2021). With moderately high shrinkage (Alipon *et al.* 2000), *G.*

apus requires proper drying schedules to minimize defects, while waterproofing is recommended to improve dimensional stability in service.

Mechanical Properties

The mean mechanical strengths are shown in Table 2 and 4. The top portion had the highest mechanical strengths, except for shear strength parallel to the grain (SS), which was greatest at the bottom. Only SS was significantly influenced by height levels ($P < 0.05$) (Table 2). Nodes had higher compression strength parallel to the grain (CS) and SS than internodes, but the differences were not statistically significant ($p > 0.05$) (Table 4).

The observed modulus of elasticity (MOE) and modulus of rupture (MOR) were lower than those reported by Nurmadina *et al.* (2017) for *G. apus*. Static bending [MOR, MOE, stress at the proportion limit (SPL)] properties increased toward the top, consistent with the findings by Nordahlia *et al.* (2011). The top portion, with higher fiber content, suits composite products like bamboo scrimber, while the bottom and middle portions are ideal for construction and furniture. Increased mechanical properties at the top portion correlate with higher RDb, vascular bundles, and fiber proportion (Maulana *et al.* 2021).

The CS of *G. apus* was lower than values reported by Hartono *et al.* (2022a) but remained highest at the top portion, due to increased RDb and vascular bundle density (Maulana *et al.* 2021b). SS (13.71 MPa) exceeded values reported by Hartono *et al.* (2022a) and Bautista *et al.* (2021) but decreased toward the top portion, consistent with Hartono *et al.* (2022a). Nodes exhibited 0.42% higher CS and 13.81% higher SS, due to shorter fiber length, higher lignin content, and denser vascular bundles.

Possible Uses of *Gigantochloa apus*

G. apus, traditionally recommended for handicrafts and furniture in the Philippines (Roxas 2012), also meets structural requirements for scaffolding, flooring, walls, and columns (Alipon & Bondad 2008; Kaminski *et al.* 2016). Additionally, it is one of the most commonly used structural bamboo species globally (Kaminski *et al.* 2016). Its culm height, diameter, wall thickness, and MOE support its use in construction and preference in Indonesia for its superior properties (Damayanto & Fefirenta 2021). It is also suitable for engineered bamboo, scrimber, hybrid laminated boards, and particleboard (Iswanto 2017).

In terms of pulp and paper production, the fiber length of *G. apus* is classified as Class I under ITAC standards (Hartono *et al.* 2022b), indicating its technical suitability for pulp applications. However, its derived ratios (RR, FR, MR, and RC) fall under Class III, and its LSF exceeds the favorable threshold, thereby limiting its papermaking potential. These characteristics suggest that pulping *G. apus* would require more intensive chemical treatments to achieve acceptable quality (Fatriasari *et al.* 2023). Thus, while *G. apus* fibers have promising length for pulp, their anatomical and derived ratio characteristics suggest greater potential in composites and reinforcement materials.

Beyond construction, *G. apus* fibers show potential for textiles, similar to species already utilized for this purpose such as *G. levis*, *B. spinosa*, and *B. vulgaris* (DOST PTRI 2021). Portal-Cahuana *et al.* (2023) likewise recommended *G. apus* for textile applications. In addition, its fibers are viable for rope production, while culm residues can be processed into pellets and charcoal briquettes (Larsen 2023). While its moderate VS may pose challenges, treatments like heat, waterproofing, and chemical preservatives enhance its stability, durability, and resistance to degradation.

CONCLUSION

This study highlights the basic properties of *G. apus* and its potential applications in the bamboo industry. Significant variation was observed along the culm, with diameter and wall thickness decreasing toward the top portion, while the bottom portion displayed longer fibers with larger diameters, wider lumens, and thicker cell walls. Derived ratios such as CWF, RR, SR, MR, RC, and LSF increased toward the top portion, whereas FR was highest at the bottom portion. Among physical properties, only RS and VS decreased significantly with height levels. For mechanical properties, static bending (MOR, MOE, SPL) showed no significant differences, though values tended to be higher at the top portion. Compression parallel to the grain was also greatest at the top portion, while shear parallel to the grain was significantly higher at the bottom portion. Between nodes and internodes, anatomical properties and derived ratios differed significantly. Nodes exhibited greater fiber diameter and thicker cell walls, along with higher CWF, RR, MR, RC, and LSF, while internodes had longer fibers, wider lumens, and higher FR and SR. These findings suggest that *G. apus* is

suitable for a wide range of applications, including furniture, handicrafts, construction materials (e.g., scaffolding, flooring, frames, and columns), and engineered composites (e.g., bamboo scrimber and hybrid laminated boards), as well as textiles, ropes, pellets, and briquettes. However, for pulp and paper production, its fiber morphology and derived ratios indicate reduced suitability without additional chemical treatment.

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