

## INFLUENCE OF CULM GEOMETRY ON THE PHYSICAL AND MECHANICAL PROPERTIES OF *BAMBUSA VULGARIS* FROM SOUTHWESTERN NIGERIA

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### Abstract:

*Bamboo offers a sustainable alternative to conventional construction materials; however, African species remain poorly characterized for engineering applications. This study evaluates the dependence of mechanical properties of Bambusa vulgaris harvested in Abeokuta, Southwestern Nigeria, on culm physical properties, including diameter, wall thickness, moisture content, and specific density. Relationships between mechanical properties (tensile strength, modulus of rupture (MOR), and modulus of elasticity in tension (MOE) and culm characteristics were systematically investigated. Fifteen culms were categorized into five diameter classes (60–110 mm) and tested in accordance with ASTM standards. Results showed that tensile strength ranged from 26.8 to 70.6 MPa, with peak values observed in small-diameter (60 mm), thin-walled (2.5 mm) specimens. MOE ranged from 0.37 to 9.51 GPa, while MOR ranged from 10.5 to 58.8 MPa. Smaller diameter classes (60–80 mm) with thinner walls exhibited significantly better mechanical performance. Wall thickness showed strong negative correlations with tensile strength ( $r = -0.68$ ,  $p < 0.01$ ) and MOR ( $r = -0.61$ ,  $p < 0.01$ ), accounting for 58% and 35% of their respective variability. In contrast, specific density exhibited positive correlations with all mechanical properties, confirming its suitability as a reliable quality indicator. Predictive regression models were developed to estimate mechanical properties from culm geometry: Tensile Strength with  $R^2$  of 0.61) and MOR with  $R^2$  of 0.53. These findings demonstrated that Nigerian Bambusa vulgaris possesses competitive mechanical properties for composite fabrication when appropriately selected based on culm geometry, and provide practical, non-destructive tools for material grading in resource-limited environments.*

**Key words:** *Bambusa vulgaris*, bamboo composites, mechanical properties, culm geometry, sustainable construction, Nigeria.

### INTRODUCTION

The demand for construction materials continues to increase globally due to rapid population growth and urbanization. In developing countries such as Nigeria, this demand places significant pressure on construction supply systems, driven by the high energy requirements of steel production, substantial CO<sub>2</sub> emissions from cement manufacturing, and depletion of timber resources resulting from deforestation (Andrew 2018; FAO 2020; Habert *et al.* 2020). These challenges highlight the urgent need for sustainable, locally available alternative materials and wooden species.

Bamboo has emerged as a promising alternative material due to its rapid growth, renewability, and favourable mechanical properties. It matures within 3–5 years and requires significantly lower processing energy compared to conventional construction materials. Previous studies have demonstrated that bamboo exhibits high strength-to-weight ratios and desirable physical and mechanical properties suitable for structural and composite applications (Faruk *et al.* 2014; Sharma *et al.* 2015). Its hierarchical microstructure, consisting of cellulose fibres embedded within a lignin matrix, forms a naturally graded composite system that contributes to its mechanical efficiency (Wegst and Ashby 2004; Gibson 2012).

The relationship between bamboo's physical structure and mechanical performance has received considerable research attention. Javadian *et al.* (2019) demonstrated that culm geometry significantly influences mechanical properties, with smaller diameter culms and higher fibre density exhibiting superior strength. Similarly, Dixon and Gibson (2014) and Huang *et al.* (2021) reported strong correlations between density gradients, fibre distribution, and mechanical behaviour, emphasizing the importance of structure–property relationships in bamboo engineering applications. *Bambusa vulgaris* is one of the most widely distributed bamboo species globally and is abundant across West Africa (Ohrnberger 1999). In Nigeria, it is commonly utilized for construction, scaffolding, and furniture production (Suleiman and Ibiyeye 2016). Despite its availability and economic importance, comprehensive engineering characterization of Nigerian *B. vulgaris* remains limited, particularly with respect to the influence of culm physical properties on mechanical performance. Most existing studies have focused on Asian species, resulting in a significant knowledge gap regarding African bamboo resources (Harries *et al.* 2012; Sharma *et al.* 2015). Furthermore, available Nigerian studies are often constrained by limited datasets, non-standardized testing methods, and insufficient statistical analysis (Ogunwusi 2012).

Bamboo exhibits inherent variability in mechanical properties due to its hierarchical structure, with fibre density and material composition varying across culm thickness and along its height. These variations significantly influence strength and stiffness and are critical for material selection in structural and composite applications. Recent studies have further confirmed that density and fibre distribution are key determinants of bamboo mechanical performance and composite behaviour (Huang *et al.* 2021; Hartono *et al.* 2022). Understanding how physical properties such as culm diameter, wall thickness, moisture content, and density influence mechanical behaviour is therefore essential for optimizing bamboo utilization.

This study addresses these gaps by systematically evaluating the physical and mechanical properties of *B. vulgaris* from Abeokuta, Southwestern Nigeria. The study investigated the relationships between culm physical properties and key mechanical parameters, including tensile strength, modulus of elasticity in tension, and modulus of rupture. In addition, predictive regression models are developed to estimate mechanical properties from simple geometric measurements. The findings provide a scientific basis for material selection and contribute to the development of bamboo as a sustainable engineering material in Nigeria.

## MATERIALS AND METHODS

### Study Area

Bamboo samples were collected from the Federal University of Agriculture, Abeokuta (FUNAAB) plantation, Ogun State, Nigeria (7°13'-7°15' N, 3°19'-3°21' E). The region is characterized with annual precipitation of 1000-1500mm, a mean temperature of approximately 27°C, and relative humidity ranging from 65% to 85%.

### Bamboo Species and Sample Collection

*B. vulgaris* was selected due to its wide distribution in Nigeria and its extensive use in traditional construction. Species identification was confirmed at the Department of Forest Resources Management Department of Federal University of Agriculture Abeokuta, Ogun State Nigeria Herbarium.

Fifteen healthy and mature culms (3-5 years old) were harvested during the dry season. Selection criteria included straight culms free from visible defects such as cracks, insect damage, and flowering. The harvested culms ranged from 10-20m in length, with outer diameters between 60 and 110mm and wall thicknesses ranging from 2 to 7mm (Fig. 1a and Fig. 1b).



a.



b.

Fig. 1.

1a: Harvested *B. vulgaris* culms at the study site; 1b: prepared specimens for mechanical testing.

The culms were transported to the laboratory and sectioned into bottom (0-5m), middle (5-10m), and top portions. Samples were collected only from the bottom and middle sections, as the top portions were not considered for the study because of their thin culm wall thickness for mechanical testing.

### Sample Preparation and Classification

From each bottom and middle section, five of 1 m subsections were obtained and split longitudinally into strips. Samples were randomly selected in accordance with ASTM D5536-10 (2010) and grouped into five diameter classes with corresponding wall thickness categories (Table 1).

Table 1

<b>Sample classification by culm diameter and wall thickness</b>			
<b>Class</b>	<b>Diameter (mm)</b>	<b>Wall Thickness (mm)</b>	<b>n</b>
1	60-70	2-3	10
2	70-80	3-4, 4-5, 5-6	30
3	80-90	3-4, 4-5, 5-6	30
4	90-100	3-4, 4-5, 5-6, 6-7	40
5	100-110	4-5, 5-6	20

### Physical Properties

#### Moisture Content (MC)

Moisture content was determined following ASTM D4442-16 (2016). Ten samples (10mm × 10mm × full wall thickness) per subsection were weighed to obtain initial mass (A), oven-dried at 103±2°C for 24 hours, and reweighed to obtain oven-dry mass (B). Moisture content was calculated as:

$$MC(\%) = \frac{A-B}{B} \times 100 [\%] \quad (1)$$

#### Specific Density (SD)

Specific density was determined in accordance with ASTM D2395-17 (2017). Sample dimensions were measured using a digital caliper (±0.01mm) to calculate volume (V), while mass (m) was measured using an analytical balance (±0.001g). Density (ρ) and specific density (SD) were calculated as:

$$\rho = \frac{m}{V} (g/mm^3) \quad (2)$$

$$SD = \rho \times 1000 \quad (g/cm^3) \quad (3)$$

### Mechanical Properties

#### Tensile Strength and Modulus of Elasticity in Tension

Tensile tests were conducted in accordance with ASTM D143-14(2014) using a Shimadzu AG-IC (Shimadzu Corporation, Kyoto Japan) universal testing machine (100kN capacity) equipped with an 80mm extensometer. Dog-bone specimens (250mm length with a reduced section width of 10mm) were prepared from internodal regions.

For specimens with wall thickness greater than 5 mm, samples were split longitudinally and results averaged. Prior to testing, specimens were conditioned at 23±2°C and 65±5% relative humidity for 7 days. Tests were performed at a constant loading rate of 1mm/min.

Tensile strength and modulus of elasticity were calculated as:

$$\sigma_t = \frac{F_{ult}}{A} (MPa) \quad (4)$$

$$E_t = \frac{\Delta\sigma}{\Delta\varepsilon} (GPa) \quad (5)$$

where:  $F_{ult}$  is the ultimate load (N) and A is cross-sectional area (mm<sup>2</sup>).

#### Modulus of Rupture and Modulus of Elasticity in Flexure

Flexural properties were determined following ASTM D4761-11 (2011) using a four-point bending configuration. Specimens (300mm length × full wall thickness × 20mm width) were prepared from internodal regions.

The loading span and support span were 240mm and 80mm, respectively. Tests were conducted at a loading rate of 2-5mm/min. Mid-span deflection was measured using a 25mm extensometer.

The modulus of rupture (MOR) and flexural modulus of elasticity ( $E_e$ ) were calculated as:

$$MOR = \frac{3P_{max}L}{2bd^2} \quad (6)$$

$$E_f = \frac{23PL^3}{108bd^3\Delta} \text{ (GPa)} \quad (7)$$

where:  $P_{max}$  is maximum load (N), L is span length (mm), b is width (mm), d is thickness (mm), and  $\Delta$  is deflection (mm).

### Statistical Analysis

Statistical analyses were conducted using SPSS version 26. Two-way analysis of variance (ANOVA) was employed to evaluate the effects of culm diameter and wall thickness on physical and mechanical properties. Duncan's multiple range test was used for post-hoc comparisons at a significance level of  $p < 0.05$ .

Pearson's correlation coefficients were used to assess relationships between physical and mechanical properties. Stepwise multiple linear regression analysis was applied to develop predictive models. Prior to analysis, normality and homogeneity of variance were verified using the Shapiro-Wilk and Levene's tests, respectively.

## RESULTS AND DISCUSSION

### Physical Properties

The physical properties of *B. vulgaris* across diameter classes and wall thicknesses are presented in Table 2. As shown in Table 2, Moisture content (MC) ranged from 12.3% to 18.9%, when the same conditions of drying were used. The lowest value was observed in Class 3 (80-90mm, 3-4mm), while the highest occurred in Class 4 (90-100mm, 4-5mm). MC increased with culm diameter. This trend is associated with anatomical variation along the culm. Larger diameter sections contain higher proportions of parenchyma tissue, which exhibit greater moisture retention compared to fibre-dominated regions (Liese 1998). Similar observations on moisture gradients in bamboo have been reported in recent structural studies (Huang et al. 2021).

Specific density (SD) ranged from 0.27 to 0.62g/cm<sup>3</sup> (Table 2) with a medium value of 0.43cm<sup>3</sup>, and statistical deviation of 0.11cm<sup>3</sup> the highest value was recorded in Class 2 (70-80mm, 4-5mm), while the lowest occurred in Class 4 (90-100mm, 5-7mm). The observed density variation reflects the distribution of vascular bundles within the culm. Fibre-rich outer regions exhibit higher density, while inner regions with increased parenchyma content show reduced density. This radial gradient has been widely reported in bamboo materials (Wegst and Ashby 2004). Recent studies confirm that fibre volume fraction governs density distribution and mechanical performance (Huang et al. 2021).

The ANOVA indicated that culm diameter significantly affected moisture content, while wall thickness was not significant ( $p = 0.062$ ). For specific density (SD), neither diameter nor thickness showed significant effects ( $p > 0.05$ ), indicating that density variation is primarily controlled by internal anatomical structure rather than external geometry.

The coefficient of variation (CV) for MC ranged from 9.1% to 11.8%, while SD ranged from 11.0% to 13.3% (Table 2). These values indicate moderate variability within classes, which is consistent with the heterogeneous structure of bamboo. Similar levels of variability have been reported for bamboo due to irregular fibre distribution along the culm (Dixon and Gibson 2014).

An inverse trend between MC and SD was observed across diameter classes. Sections with higher MC generally exhibited lower SD, particularly in larger diameter classes. This relationship reflects increased parenchyma content and reduced fibre concentration in these regions. Comparable relationships between moisture, density, and anatomical composition have been reported in bamboo studies (Sharma et al. 2015). From a material selection perspective, lower MC and higher SD observed in Classes 1-3 indicate better suitability for structural applications.

Table 2

**Physical Properties of *B. vulgaris* by Diameter Class and Wall Thickness**

Diameter Class (mm)	Wall Thickness (mm)	n	MC (%) Mean $\pm$ SD	CV%	SD (g/cm <sup>3</sup> ) Mean $\pm$ SD	CV%
60-70 (Class 1)	2-3	10	13.70 $\pm$ 1.24	9.1	0.47 $\pm$ 0.052	11.1
70-80 (Class 2)	3-4	10	14.30 $\pm$ 1.52	10.6	0.52 $\pm$ 0.061	11.7
	4-5	10	15.80 $\pm$ 1.87	11.8	0.62 $\pm$ 0.068	11.0
	5-6	10	14.60 $\pm$ 1.43	9.8	0.47 $\pm$ 0.055	11.7

<b>80-90 (Class 3)</b>	3-4	10	12.30 ± 1.18	9.6	0.58 ± 0.064	11.0
	4-5	10	13.30 ± 1.35	10.2	0.32 ± 0.041	12.8
	5-6	10	14.10 ± 1.46	10.4	0.49 ± 0.057	11.6
<b>90-100 (Class 4)</b>	3-4	10	17.20 ± 1.92	11.2	0.44 ± 0.051	11.6
	4-5	10	18.90 ± 2.11	11.2	0.34 ± 0.043	12.6
	5-6	10	18.60 ± 2.04	11.0	0.27 ± 0.036	13.3
	6-7	10	15.30 ± 1.67	10.9	0.27 ± 0.035	13.0
<b>100-110 (Class 5)</b>	4-5	10	14.10 ± 1.38	9.8	0.36 ± 0.042	11.7
	5-6	10	16.40 ± 1.73	10.5	0.38 ± 0.044	11.6

### Mechanical Properties

The mechanical properties of *B. vulgaris* across diameter and wall thickness classes are presented in Table 3. The result showed that, tensile strength ranged from 26.8 to 70.6 MPa with a medium value of 41.0 MPa, with the highest value recorded in Class 1 (60mm, 2.5mm) and the lowest in Class 4 (90mm, 6.5mm). It was observed that tensile strength decreased with increasing culm diameter and wall thickness. This observed trend in this study could be associated with fibre distribution within the culm. According to Amada *et al.*, (1997) and Ghavami (2005), thinner sections mostly contain higher fibre concentration and better fibre alignment, resulting in improved tensile performance. The reduction observed in thicker sections could also be attributed to increased parenchyma content, which contributes minimally to load-bearing capacity. Similar relationships have been reported in this study between fibre volume fraction and tensile strength have been reported in recent studies (Huang *et al.* 2021).

The variability in tensile strength, as indicated by standard deviations in Table 3, reflects the heterogeneous structure of bamboo. This variability is consistent with reported differences in fibre continuity and local structural defects (Javadian *et al.* 2019).

The modulus of elasticity (MOE) ranged from 0.37 to 9.51 GPa, with a medium value of 1.92 GPa with the highest value observed in Class 3 (80mm, 3.5mm) and the lowest in Class 4 (90mm, 6.5mm). The variation in MOE indicates sensitivity to structural heterogeneity. Stiffness is influenced by fibre alignment, bonding within the cell wall, and the distribution of reinforcing fibres. The higher MOE observed in moderate diameter classes suggests a more balanced fibre structure, while lower values in thicker sections reflect increased matrix contribution and reduced fibre efficiency. Similar observations have been reported for bamboo stiffness behaviour (Dixon and Gibson 2014; Huang *et al.* 2021).

Modulus of rupture (MOR) ranged from 10.5 to 58.8 MPa, with the highest value recorded in Class 1 (2-3mm) and the lowest in Class 4 (6-7mm). A consistent decrease in MOR with increasing wall thickness was observed across all diameter classes. This reduction could be attributed to the functional gradient structure of bamboo. In bending, stress is concentrated at the outer fibres, where fibre density is highest. Increasing wall thickness introduces a larger proportion of inner regions with lower fibre density, thereby reducing flexural performance (Wegst and Ashby 2004). Similar trends have been reported in bamboo flexural behaviour (Sharma *et al.* 2015).

A positive relationship between tensile strength and MOR was observed, indicating that both properties are governed by fibre density and distribution. Sections with higher tensile strength generally exhibited higher flexural performance, confirming the role of fibre continuity in mechanical behaviour (Youssefian and Rahbar 2015).

From an application perspective, culms within Classes 1-3 (60-80mm diameter, thinner walls) exhibited superior mechanical performance. These sections are therefore more suitable for structural and composite applications. In contrast, larger diameter culms with thicker walls showed reduced mechanical efficiency.

Table 3

**Mechanical Properties of *B. vulgaris* by Diameter Class and Wall Thickness**

Diameter (mm)	Thickness (mm)	Area (mm <sup>2</sup> )	Force (kN)	TS (MPa)	MOE (GPa)	MOR (MPa)
				Mean ± SD	Mean ± SD	Mean ± SD
<b>60</b>	2.5	50	3.00-3.53	64.9 ± 5.4	3.44 ± 2.51	58.8 ± 6.1
	<b>70</b>	3.5	70	2.70-3.30	44.1 ± 4.7	2.65 ± 1.53
<b>80</b>	4.5	90	2.70-3.30	34.3 ± 3.8	1.43 ± 1.62	26.0 ± 2.8
	5.5	110	3.70-4.30	36.4 ± 3.9	0.64 ± 0.30	15.0 ± 1.7
	3.5	70	3.10-3.70	48.1 ± 4.3	6.65 ± 3.43	33.0 ± 3.5
	4.5	90	2.70-3.40	34.7 ± 4.1	0.81 ± 0.44	14.0 ± 1.6
	5.5	110	3.30-4.35	35.3 ± 4.8	0.78 ± 0.21	26.1 ± 2.8

<b>90</b>	3.5	70	3.16-4.08	50.2 ± 6.9	1.16 ± 0.39	27.8 ± 3.0
	4.5	90	3.29-3.90	39.9 ± 3.4	0.86 ± 0.46	16.5 ± 1.8
	5.5	110	3.74-4.01	35.4 ± 1.3	1.58 ± 1.26	10.7 ± 1.2
	6.5	130	3.48-4.14	28.9 ± 2.6	0.80 ± 0.50	10.5 ± 1.1
<b>100</b>	4.5	90	4.21-4.55	48.8 ± 1.9	0.83 ± 0.44	32.4 ± 3.4
	5.5	110	3.31-4.02	32.8 ± 3.3	3.25 ± 3.77	18.0 ± 2.0

### Analysis of Variance (ANOVA) and Post-hoc Comparisons

The results of the ANOVA for mechanical properties are presented on Table 4, while the Duncan's multiple range test results are shown on Table 5.

The ANOVA results indicate that wall thickness had a significant effect on modulus of elasticity and modulus of rupture. In contrast, culm diameter did not show significant effects, although moderate effect sizes were observed. The dominance of wall thickness reflects its direct relationship with fibre distribution. Thinner walls contain a higher proportion of load-bearing fibres, while thicker walls include more parenchyma tissue, reducing mechanical efficiency (Wegst and Ashby 2004). Similar findings have been reported in recent bamboo studies linking wall thickness to fibre volume fraction and strength (Huang *et al.* 2021).

The effect size ( $\eta^2$ ) indicates that wall thickness accounted for 24% of the variation in MOE and 35% in MOR, confirming a moderate to strong practical influence. Culm diameter contributed less to variability, suggesting a secondary role.

The interaction between diameter and wall thickness was not significant indicating that their effects are largely independent. This suggests that fibre distribution associated with wall thickness governs mechanical performance regardless of culm size as reported by Dixon and Gibson (2014).

The post-hoc results provided further clarification of these differences. For moisture content (MC), three homogeneous groups were identified. Classes 1 and 3 exhibited the lowest values ( $\approx 13.2$ - $13.7\%$ ), Classes 2 and 5 formed an intermediate group ( $\approx 14.9$ - $15.3\%$ ), while Class 4 showed significantly higher MC ( $\approx 17.5\%$ ).

This pattern reflects anatomical variation, where larger diameter culms contain higher parenchyma content and retain more moisture content (Liese 1998).

For specific density (SD), overlapping subsets were observed across diameter classes, indicating gradual variation. Class 1 exhibited the highest density, while Class 4 showed the lowest. This supports the ANOVA result, suggesting that density is influenced by internal structure rather than a single geometric parameter (Dixon and Gibson 2014).

For modulus of rupture (MOR), Class 1 formed a distinct group with significantly higher values ( $\approx 58.8$  MPa), while Classes 2-5 showed overlapping and lower values ( $\approx 16.4$ - $25.2$  MPa). This confirms that smaller diameter culms exhibit superior flexural performance.

The separation of Class 1 is attributed to higher fibre concentration at the outer culm wall, which governs resistance to bending stresses (Wegst and Ashby 2004). Similar behaviour has been reported for bamboo flexural properties (Sharma *et al.* 2015).

Overall, the ANOVA and post-hoc results confirm that wall thickness is the primary factor controlling mechanical performance, while culm diameter plays a secondary role. The post-hoc grouping further demonstrates that smaller diameter culms with thinner walls provide superior structural performance.

From a material selection perspective, culms within Classes 1-3 are more suitable for structural applications, while larger diameter classes may be limited to non-load-bearing uses.

Table 4

<i>Two-way ANOVA Results for Mechanical Properties</i>							
Property	Source	Sum of Squares	df	Mean Square	F	P	$\eta^2$
<b>MOE (Tension)</b>	Culm diameter	28.4	4	7.1	2.15	0.092	0.18
	Wall thickness	42.6	3	14.2	4.31	0.010	0.24
	Diameter × Thickness	36.8	8	4.6	1.39	0.231	0.22
	Error	131.8	40	3.3			
<b>MOR</b>	Culm diameter	485.7	4	121.4	2.34	0.097	0.21
	Wall thickness	946.0	3	315.3	4.56	0.011	0.35
	Diameter × Thickness	628.0	8	78.5	1.82	0.145	0.26
	Error	1,798.2	40	45.0			

Table 5

**Post-hoc Comparisons (Duncan's Test) for Physical and Mechanical Properties**

Parameter	Diameter Class (mm)	Mean Value
MC (%)	80-90 (Class 3)	13.17 <sup>a</sup>
	60-70 (Class 1)	13.70 <sup>a</sup>
	70-80 (Class 2)	14.89 <sup>b</sup>
	100-110 (Class 5)	15.28 <sup>b</sup>
	90-100 (Class 4)	17.51 <sup>c</sup>
SD (g/cm <sup>3</sup> )	90-100 (Class 4)	0.33 <sup>a</sup>
	70-80 (Class 2)	0.37 <sup>ab</sup>
	80-90 (Class 3)	0.46 <sup>abc</sup>
	100-110 (Class 5)	0.47 <sup>abc</sup>
	60-70 (Class 1)	0.54 <sup>c</sup>
MOR (MPa)	90-100 (Class 4)	16.4 <sup>b</sup>
	70-80 (Class 2)	19.6 <sup>b</sup>
	80-90 (Class 3)	24.4 <sup>b</sup>
	100-110 (Class 5)	25.2 <sup>b</sup>
	60-70 (Class 1)	58.8 <sup>a</sup>

Value with the same alphabet are no significantly different

**Correlation and Regression Analysis**

The relationships between physical and mechanical properties of *B. vulgaris* and the corresponding predictive models are presented in Tables 6 and 7. The result of Pearson correlation analysis revealed significant relationships between culm properties and mechanical performance. Wall thickness showed strong negative correlations with tensile strength ( $r = -0.68$ ,  $p < 0.01$ ) and modulus of rupture ( $r = -0.61$ ,  $p < 0.01$ ), indicating a reduction in mechanical performance with increasing thickness.

This relationship reflects fibre distribution within the culm. Thicker sections contain higher proportions of parenchyma tissue, reducing the contribution of load-bearing fibres (Wegst and Ashby 2004). Similar trends have been reported in bamboo studies relating fibre volume fraction to strength (Sharma *et al.* 2015). Specific density showed moderate positive correlations with tensile strength ( $r = 0.57$ ,  $p < 0.01$ ) and MOR ( $r = 0.46$ ,  $p < 0.01$ ), indicating improved performance in denser material. Density reflects fibre content and is widely recognized as a key indicator of mechanical behaviour (Huang *et al.* 2021).

Culm diameter exhibited moderate negative correlations with tensile strength ( $r = -0.45$ ,  $p < 0.01$ ) and MOR ( $r = -0.37$ ,  $p < 0.05$ ), while showing a positive correlation with wall thickness ( $r = 0.51$ ,  $p < 0.01$ ). This indicates that the effect of diameter on mechanical properties is largely indirect through its association with wall thickness. A positive relationship was also observed among mechanical properties. Tensile strength correlated with MOR ( $r = 0.52$ ,  $p < 0.01$ ) and MOE ( $r = 0.48$ ,  $p < 0.01$ ), confirming that fibre density and distribution govern overall mechanical behaviour (Youssefian and Rahbar 2015).

Based on these relationships, multiple linear regression models were developed to predict mechanical properties using culm diameter (D) and wall thickness (t). The models are expressed as:

$$TS \text{ (MPa)} = 82.4 - 7.8t - 0.15D$$

$$MOR \text{ (MPa)} = 71.3 - 6.2t - 0.21D$$

$$MOE \text{ (GPa)} = 7.2 - 1.1t - 0.02D$$

The models explained a substantial proportion of variability in mechanical properties, with R<sup>2</sup> values of 0.61 for tensile strength and 0.53 for MOR, while MOE showed lower predictability (R<sup>2</sup> = 0.32).

The regression coefficients indicated that wall thickness has a stronger influence than culm diameter. Each 1mm increase in wall thickness resulted in reductions of approximately 7.8 MPa in tensile strength, 6.2 MPa in MOR, and 1.1 GPa in MOE. This confirms the dominant role of wall thickness identified in the correlation and ANOVA analyses.

The lower predictive accuracy for MOE reflects its sensitivity to microstructural factors such as fibre orientation and bonding, which are not fully captured by geometric parameters (Huang *et al.* 2021).

The statistical significance of the models ( $p < 0.001$ ) and low standard errors indicate good reliability. Predicted values were consistent with observed ranges, confirming model validity.

From an application perspective, these models provide a practical tool for estimating mechanical properties from simple measurements. This enables rapid, non-destructive assessment of bamboo quality, which is particularly useful in field conditions.

Overall, the combined correlation and regression analysis confirms that mechanical performance in *B. vulgaris* is primarily controlled by wall thickness and density. The predictive models developed provide a basis for material grading and selection in structural and composite applications.

Table 6

**Pearson Correlation Coefficients Between Physical and Mechanical Properties**

Parameter	Tensile Strength	MOR	MOE	Wall Thickness	Culm Diameter
Tensile Strength	1				
MOR	0.52**	1			
MOE	0.48**	0.34*	1		
Wall Thickness	-0.68**	-0.61**	-0.53**	1	
Culm Diameter	-0.45**	-0.37*	-0.01	0.51**	1

\*\*Correlation is significant at the 0.01 level (2-tailed). \*Correlation is significant at the 0.05 level (2-tailed).

Table 7

**Multiple Linear Regression Models for Predicting Mechanical Properties**

Property	Model Equation	R <sup>2</sup>	Adjusted R <sup>2</sup>	SE	p-value
Tensile Strength (MPa)	TS = 82.4 - 7.8t - 0.15D	0.61	0.58	8.2 MPa	<0.001
MOR (MPa)	MOR = 71.3 - 6.2t - 0.21D	0.53	0.50	7.5 MPa	<0.001
MOE (GPa)	MOE = 7.2 - 1.1t - 0.02D	0.32	0.28	2.1 GPa	0.004

where: t = wall thickness (mm) and D = culm diameter (mm); SE = Standard Error

### Influence of Culm Structure on Mechanical Behavior

The results of this study showed that mechanical performance of *B. vulgaris* is primarily controlled by culm structure, particularly wall thickness and fibre distribution. The observed decrease in tensile strength and modulus of rupture with increasing wall thickness (Tables 3 and 6) indicates that structural efficiency is governed by internal composition rather than external geometry.

This trend is consistent with the functionally graded structure of bamboo, where fibre concentration decreases from the outer to inner regions of the culm wall. The outer region contains densely packed vascular bundles, while the inner region is dominated by parenchyma tissue with limited mechanical contribution (Wegst and Ashby 2004; Dixon and Gibson 2014). As wall thickness increases, the proportion of low-density parenchyma increases, resulting in reduced strength and stiffness.

Similar relationships between fibre distribution and mechanical behaviour have been reported across bamboo species. Studies on *Phyllostachys edulis* and *Dendrocalamus asper* showed that fibre volume fraction is the primary determinant of strength and stiffness, independent of culm size (Javadian *et al.* 2019; Huang *et al.* 2021; Zhang *et al.* 2021). The present results follow the same structural trend.

### Role of Density and Moisture Content

The results show that specific density is positively associated with mechanical performance, while moisture content shows an inverse trend (Tables 2 and 6). Sections with higher density exhibited higher tensile strength and modulus of rupture, indicating that density reflects fibre concentration and load-bearing capacity.

This relationship is consistent with the role of fibre volume fraction in bamboo mechanics. Higher density corresponds to increased vascular bundle concentration and higher cellulose content, which contribute to improved strength (Sharma *et al.* 2015; Huang *et al.* 2021). The moderate correlations observed between density and mechanical properties (Table 6) supports this relationship.

Moisture content increased with culm diameter (Table 2), and higher values were associated with lower density and reduced mechanical performance. This reflects increased parenchyma content and porosity in larger diameter culms. Similar relationships between moisture, density, and anatomical structure have been reported in bamboo materials (Liese 1998; Sharma *et al.* 2015; Huang *et al.* 2021).

The inverse relationship between moisture content and density observed in this study indicates that anatomical composition governs both physical and mechanical properties.

### Tensile and Flexural Behavior

The tensile strength and modulus of rupture decreased with increasing wall thickness across all diameter classes (Table 3). This indicates that mechanical behaviour is governed by fibre distribution rather than material volume.

Fibre bundles act as the primary load-bearing elements in bamboo. Sections with higher fibre concentration and alignment exhibit improved tensile and flexural performance. The higher strength values observed in Classes 1-3 are therefore associated with higher fibre efficiency.

Similar trends have been reported in bamboo mechanics. Javadian *et al.* (2019) showed that smaller culm sections with higher fibre density exhibit improved strength, while Huang *et al.* (2021) reported that fibre distribution controls both tensile and flexural properties. Sharma *et al.* (2015) also observed reductions in strength with increasing wall thickness due to increased parenchyma content.

The positive relationship observed between tensile strength and modulus of rupture (Table 6) indicates that both properties are controlled by the same structural factors, primarily fibre density and distribution (Youssefian and Rahbar 2015; Huang *et al.* 2021).

The variation in modulus of elasticity reflects sensitivity to structural heterogeneity. Lower MOE values in thicker sections indicate reduced fibre contribution and increased matrix influence, consistent with previous observations (Dixon and Gibson 2014; Huang *et al.* 2021).

### **Statistical and Predictive Relationships**

The ANOVA results (Table 4) show that wall thickness significantly affects modulus of elasticity and modulus of rupture, while culm diameter does not show significant effects. This indicates that mechanical performance is primarily controlled by wall thickness rather than overall culm size.

The non-significant interaction between diameter and thickness suggests that their effects are independent, with wall thickness representing the dominant structural parameter. Similar findings have been reported in studies linking fibre distribution to mechanical behaviour (Dixon and Gibson 2014; Huang *et al.* 2021).

Correlation analysis (Table 6) confirms that wall thickness has a strong negative relationship with tensile strength and MOR, while density shows positive relationships with these properties. Culm diameter shows weaker relationships, indicating that its effect is indirect through its association with wall thickness.

The regression models developed (Table 7) shows that wall thickness has a greater influence than diameter, as reflected in the regression coefficients. The models explain a substantial proportion of variability in tensile strength and MOR ( $R^2 = 0.61$  and  $0.53$ ), indicating that simple geometric parameters can be used to estimate mechanical properties.

Similar predictive approaches have been reported for bamboo materials, where geometric and density parameters are used to estimate strength and stiffness (Javadian *et al.* 2019; Huang *et al.* 2021). The lower predictive accuracy for MOE reflects its dependence on microstructural factors not captured by geometric measurements.

### **Implications for Material Selection**

The results indicate that culms within the diameter range of 60-80mm and wall thickness of 2-4mm exhibit higher mechanical performance. These sections combine higher density, lower moisture content, and improved fibre distribution.

The regression models provide a practical tool for estimating mechanical properties using simple measurements of diameter and wall thickness. This enables rapid, non-destructive assessment of bamboo materials.

Similar approaches have been proposed for bamboo material grading and selection, where fibre-rich sections are preferred for structural applications such as load bearing components (Huang *et al.* 2021; Zhang *et al.* 2021). The present results support these approaches and provide data specific to *B. vulgaris* from Nigeria.

### **CONCLUSIONS**

The physico-mechanical properties of *Bambusa vulgaris* from Southwestern Nigeria were evaluated in relation to culm physical characteristics. The results showed that mechanical performance is primarily influenced by wall thickness and specific density, while culm diameter has a secondary effect.

Moisture content ranged from 12.3 to 18.9% and increased with culm diameter. Specific density ranged from 0.27 to 0.62g/cm<sup>3</sup> and showed a positive relationship with mechanical properties. Tensile strength (26.8-70.6 MPa), modulus of elasticity (0.37-9.51 GPa), and modulus of rupture (10.5-58.8 MPa) decreased with increasing wall thickness, indicating that fibre distribution within the culm governs mechanical behaviour.

Statistical analysis confirmed that wall thickness is the dominant factor affecting mechanical properties, with significant effects observed for modulus of elasticity and modulus of rupture. Correlation analysis showed strong negative relationships between wall thickness and strength, and positive relationships between density and mechanical performance.

The regression models developed demonstrates that mechanical properties can be estimated from simple geometric parameters, providing a basis for non-destructive material evaluation.

Based on the results, culms with diameters of 60-80mm and wall thickness of 2-4mm exhibit superior mechanical performance and are suitable for structural and composite applications. These findings provide

quantitative data for the selection and utilization of *B. vulgaris* and support its potential as a sustainable engineering material in Nigeria.

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