

RELATIONSHIP BETWEEN FIBER MORPHOLOGY AND PARALLEL-TO-GRAIN MECHANICAL STRENGTH IN FOUR BAMBOO SPECIES GROWN IN THE PHILIPPINES

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ARTICLE HIGHLIGHTS

- The study evaluated the fiber morphology and mechanical properties of four bamboo species, revealing the species-specific relationships of fiber traits and mechanical performance.
- Cell wall thickness and lumen width influenced bamboo's mechanical strength.
- Solid bamboo exhibits the highest compression despite weak fiber links; Yellow bamboo displays the highest shear with the longest fibers; Thailand bamboo demonstrates the strongest fiber traits-strength correlations.

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ABSTRACT

The compression and shear strength parallel to the grain of four bamboo species namely Yellow bamboo (*Bambusa vulgaris* Schrad. ex J.C.Wendl.), Iron bamboo (*Guadua angustifolia* Kunt.), Solid bamboo [*Dendrocalamus strictus* (Roxb.) Nees], and Thailand bamboo (*Thyrsostachys siamensis* Gamble) were evaluated in relation to their fiber morphology. A total of 24 mature culms (4 – 5 years old) were collected, and 36 samples per species were prepared for compression and shear strength tests following ISO 22157:2019, with specimen height equal to 10 × the culm wall thickness. For fiber morphology, matchstick-sized pieces were macerated in a 1:1 solution of acetic acid and hydrogen peroxide at 100 °C for 3 – 5 hours, after which 25 intact fibers per replicate were examined under a Zeiss Primo Star microscope and measured using Zen Lite software following International Association of Wood Anatomists standards. Results revealed distinct species-specific patterns. Thailand bamboo exhibited the strongest positive correlations, particularly between fiber length, fiber diameter, cell wall thickness, and both strength properties. Yellow bamboo recorded the longest fibers (2367.97 µm) and the highest shear strength (15.03 MPa), with strong associations to cell wall thickness. In contrast, Solid bamboo showed the highest compression strength (46.16 MPa) but weak correlations with fiber characteristics, while Iron bamboo demonstrated moderate associations between fiber morphology and mechanical properties. Among all fiber characteristics, cell wall thickness consistently showed a strong positive correlation with strength across species, whereas lumen width was negatively correlated, indicating that denser, more compact fiber structures enhance load-bearing capacity. Principal Component Analysis (PCA) showed that PC1 and PC2 explained substantial variation across species (e.g., up to 53.7% and 19.3% in Thailand bamboo), confirming the dominant influence of cell wall thickness on mechanical performance. These findings highlight the anatomical basis of bamboo's mechanical performance and emphasize the need for species-specific approaches in its structural utilization.

Keywords: Cell wall thickness, fiber diameter, fiber length, lumen width, mechanical properties

INTRODUCTION

Bamboo has emerged as a sustainable alternative to traditional timber, offering solutions to the dual challenges of resource scarcity and environmental degradation. Globally, bamboo covers approximately 35 million ha and thrives in marginal, degraded, or agricultural lands, conditions typically unsuitable for conventional forest plantations (INBAR 2023). Its rapid growth, high biomass yield, and low input requirements make it an ideal candidate for ecological rehabilitation and material substitution. Furthermore, bamboo's excellent mechanical properties, particularly its high strength-to-weight ratio and durability, make it comparable to materials like steel, wood, and concrete in structural applications (Manandhar *et al.* 2019). In the Philippines, more than 1,500 bamboo species have been recorded under 75 genera (Baja-Lapis *et al.* 2016). Of these, several species including Yellow bamboo (*Bambusa vulgaris* Schrad. ex J.C.Wendl.), Iron bamboo (*Guadua angustifolia* Kunt.), Solid bamboo [*Dendrocalamus strictus* (Roxb.) Nees], and Thailand bamboo (*Thyrsostachys siamensis* Gamble) have been recognized for their potential. These species are increasingly cultivated in plantations and urban landscape due to their favorable growth characteristics, aesthetic value, and broad application across construction, furniture, and handicraft industries (Roxas 2012; Hillary *et al.* 2022). Each species exhibits unique culm properties. Yellow bamboo is widely used for decorative and utility products due to its vibrant color and flexibility (Nfornekah *et al.* 2020; Maviton *et al.* 2023). Iron bamboo, native to Latin America, is known for its exceptional strength and resistance, making it ideal for engineered applications (Londoño 2001; Bornoma *et al.* 2016). Solid bamboo is recognized for its dense culms, offering high compressive strength ideal for scaffolding, beams, and structural panels (Bhonde *et al.* 2014). Thailand bamboo, with its slim culms and edible shoots, serves a dual purpose in both food and construction sectors (Roxas 2012). Moreover, these four bamboo species were primarily selected to capture a wide scale of the increasingly cultivated bamboo species in the Philippines with contrasting culm properties, such as flexibility in Yellow bamboo, exceptional strength in Iron bamboo, high density and compressive strength in Solid bamboo, and dual-purpose utility in Thailand bamboo, enabling a comprehensive comparative analysis of the relationship between

anatomical traits and mechanical performance across species with multi-structural characteristics and applications.

Although these species are widely cultivated, limited studies have explored how their anatomical traits such as fiber length, diameter, lumen width, and cell wall thickness influence mechanical performance. Previous studies highlight the significance of anatomical characteristics in determining bamboo strength. For instance, Mohmod *et al.* (1990) investigated *Bambusa spinosa*, *B. vulgaris* var. *striata*, and *Gigantochloa scortechinii* and found that cell wall thickness showed strong positive correlation with compression strength, while lumen width was more closely associated with shear resistance. On the other hand, Mohmod *et al.* (1993) reported that most mechanical properties including compression and shear strength increased with thicker cell walls in *B. spinosa*. Wahab *et al.* (2012) further demonstrated that in *G. scortechinii*, cell wall thickness influenced shear strength. Similarly, Wahab *et al.* (2018) emphasized that shear strength of *B. vulgaris* varied with anatomical position and fiber geometry, with higher strength observed in samples with thicker cell walls. Moreover, Espiloy *et al.* (1986) reported that fiber characteristics have influence on the mechanical properties of *B. spinosa*, and *G. levis*.

To bridge this gap, the present study investigates the relationship between fiber morphological characteristics (fiber length, diameter, lumen width, and cell wall thickness) and the mechanical properties, specifically compression and shear strength parallel to the grain of Yellow bamboo, Iron bamboo, Solid bamboo, and Thailand bamboo. Establishing these relationships aims to deepen the understanding of how fiber characteristics influence the mechanical behavior of bamboo. This knowledge will serve as a foundation for future research and development efforts focused on optimizing bamboo utilization across various structural and industrial applications.

MATERIALS AND METHODS

Sample Collection

A total of 24 mature culms were collected, consisting of six culms each from four bamboo species: Yellow bamboo (*Bambusa vulgaris* Schrad. ex J.C.Wendl.), Iron bamboo (*Guadua angustifolia* Kunt.), Solid bamboo [*Dendrocalamus strictus* (Roxb.) Nees], and Thailand bamboo (*Thyrsostachys siamensis* Gamble) (Fig. 1).



Figure 1 Clumps of bamboo species used in the study
Notes: A = Yellow Bamboo; B = Iron Bamboo; C = Solid Bamboo; D = Thailand Bamboo.

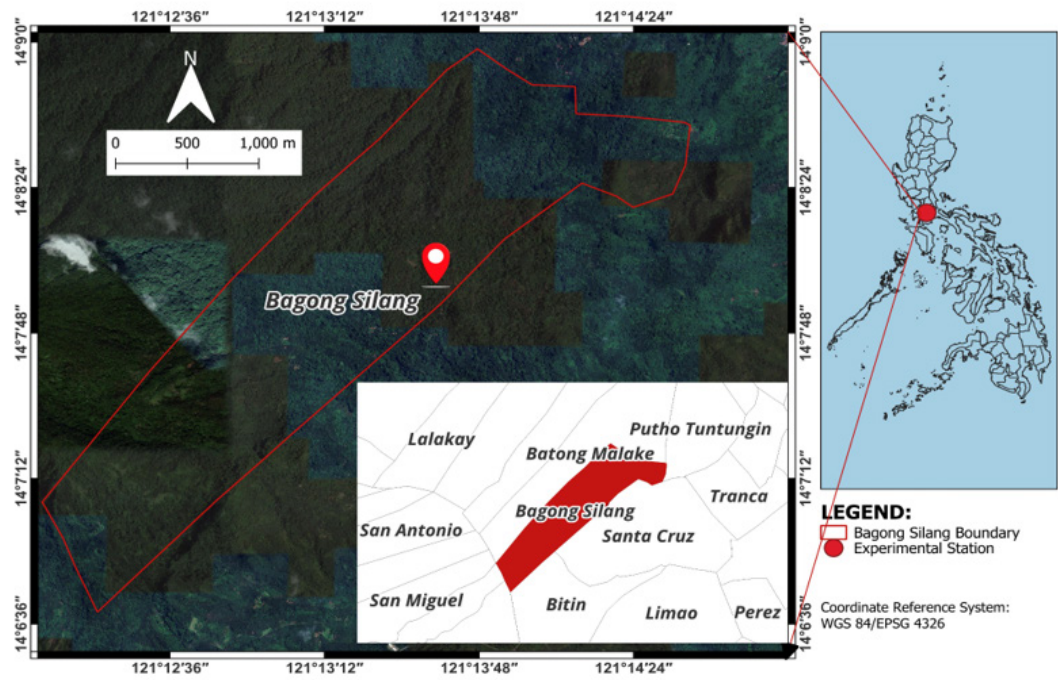


Figure 2 Collection site of bamboo species in Mount Makiling Forest Reserve, Los Banos, Laguna

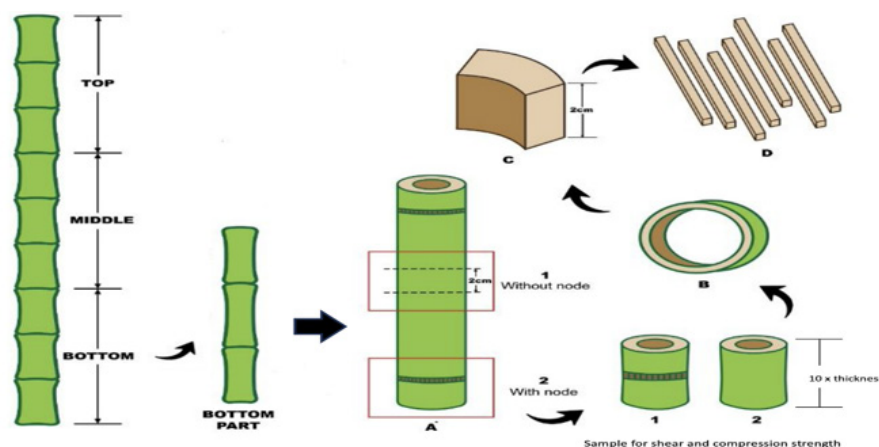


Figure 3 Sampling scheme used in the study

Notes: A = showing the based portion of the culm where the sample where collected; B = Culm ring sample for fiber morphology; C & D = Sample used for fiber morphology analysis.

The culms were harvested from different clumps. The samples were obtained from the Los Baños Experimental Station managed by the Department of Environment and Natural Resources – Ecosystems Research and Development Bureau (DENR-ERDB) (Fig. 2). The site is located at an elevation of approximately 400 m asl. The estimated age of the culms was 4 - 5 years old, determined based on visual indicators of maturity, including changes in internode color and texture, the presence of epiphytes, persistent culm sheaths, sheath rings at the nodes, and characteristic branching patterns (Santos 2018).

Each culm was cut approximately 30 cm above the ground and measured in full length. The culm was then divided into three equal segments - bottom, middle, and top. At the base of each segment, two samples were extracted, one from the internode and one from the node (Fig. 3). These were used to evaluate compression and shear strength parallel to the grain. After mechanical testing, a cross-sectional ring measuring 25.4 mm in height was obtained from each sampling point. These rings were then used for fiber morphology analysis.

Compression and Shear Strength Determination

A total of 36 samples per species were prepared for the compression and shear strength tests parallel to the grain, resulting in a total of 144 specimens across the four bamboo species. The compression and shear strength samples parallel to the grain tests were prepared following ISO 22157:2019, with specimen height equal to $10 \times$ the culm wall thickness. Four measurements were taken at equal

intervals of 90° around the culm circumference to determine the wall thickness accurately, and the average value was used. Mechanical testing was conducted using a Shimadzu UHX 300 kN universal testing machine (Shimadzu Corp., Japan), operating at a constant crosshead speed of 0.6 mm per minute for both compression and shear tests.

Fiber Maceration

From the 25.4 mm culm ring, small bamboo chips were first prepared and trimmed into matchstick-sized pieces (Fig. 3). These were then subjected to a delignification process using a solution of equal parts 50% acetic acid and 50% hydrogen peroxide. The samples were heated in a water bath for 3 to 5 hours at 100°C , or until they turned soft and white, indicating that the fibers had sufficiently separated (Espiloy *et al.* 1999). Once softened, the samples were thoroughly rinsed with distilled water to remove any acid remains. The cleaned fibers were then observed and measured under a microscope with safranin.

Fiber Measurement

To ensure proper separation of structural elements, the macerated fiber samples were agitated while inside the test tubes. The dispersed fibers were then mounted on microscope slides and examined under a Zeiss Primo Star microscope equipped with a digital camera. Fiber images acquisition and measurements were performed using Zen Lite software, following the procedure described by Villareal *et al.* (2020). Also, calibration was performed using a stage micrometer (1 mm divided into 100 units, $10\ \mu\text{m}$ per division) prior to imaging session to ensure accuracy. Fiber length

was measured under 10x magnification, while fiber diameter and lumen diameter were measured under 40x magnification. The measurement setup and orientation are illustrated in Figure 4.

For each sampling point (node and internode from the bottom, middle, and top sections of each culm), twenty-five (25) intact and undamaged fibers were randomly selected and measured. This resulted in a total of 900 fibers per species and 3,600 fibers across all four bamboo species. The fiber length, fiber diameter, and lumen width were measured following the standards of the International Association of Wood Anatomists (IAWA) (Wheeler *et al.* 1989). Fiber diameter and lumen width were measured across the shortest axis of the fiber to minimize the effect of flattening during slide preparation. The cell wall thickness was half the difference between the fiber diameter and lumen width.

Statistical Analysis

All statistical analyses were conducted using RStudio version 4.2.1 (R Core Team 2022). Descriptive statistics were computed to summarize the fiber morphological properties (i.e., length, diameter, lumen width, cell wall thickness) and the compression and shear strength parallel to the grain of bamboo samples. The unit of observation was based on specimen-level mean values. Specifically, for each sampling point (node and internode from the bottom, middle, and top), fiber measurements were averaged from 25 individual fibers. These mean values were then used in all subsequent analyses

to ensure consistency with the corresponding mechanical test data. The correlation analysis and PCA were performed using 36 observations per species ($n = 36$), corresponding to specimen-level mean values derived from each sampling point ($6 \text{ culms} \times 3 \text{ sections} \times 2 \text{ positions}$). Across the four species, this resulted in a total of 144 observations. Pearson's correlation coefficients were conducted separately for each species to evaluate the associations between fiber morphology and mechanical strength. Statistical significance was assessed at the 95% confidence level ($P < 0.05$).

Principal Component Analysis (PCA) was performed for each species using the specimen-level mean values to explore multivariate relationships among traits. Before analysis, all variables were standardized by mean-centering and scaling to unit variance to eliminate the influence of differing measurement scales. The first two principal components (PC1 and PC2) were extracted for visualization and interpretation. The PCA was based on 36 observations per species ($n = 36$), derived from specimen-level mean values, thereby representing variation within each bamboo species. PCA biplots were used to illustrate the distribution of samples along PC1 and PC2, with trait vectors representing the direction and magnitude of each variable's contribution. In addition, loading plots were generated to show the relative contribution of each trait to the principal components, with vector color intensity scaled by percentage contribution.

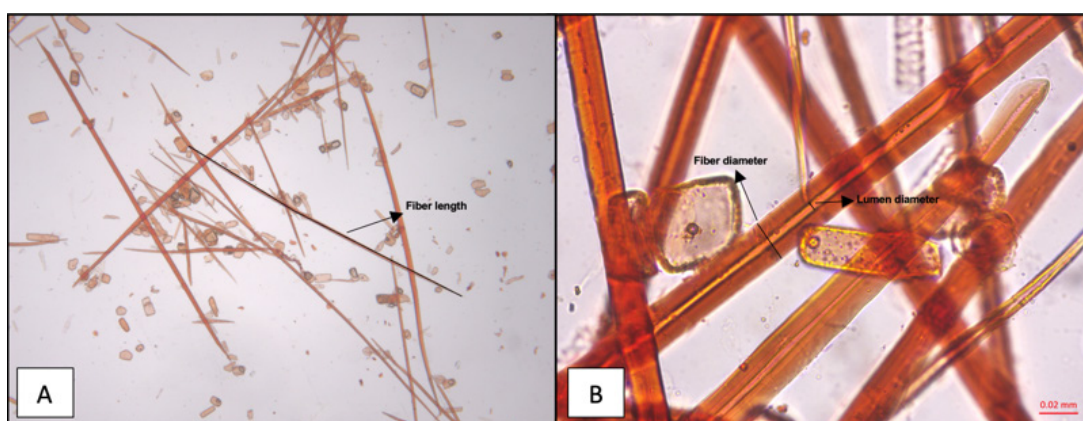


Figure 4 Measurement of fiber morphology from macerated bamboo samples

Notes: A = fiber length along the longitudinal axis; B = fiber and lumen diameters across the transverse axis.

RESULTS AND DISCUSSION

Fiber Morphology and Mechanical Properties

The fiber morphology and mechanical properties of the four bamboo species are shown in Figure 5. Figures 6 and 7 shows sample of fiber photographs of the four species. Among the species, Yellow bamboo exhibited the longest fibers, with an average length of 2,367.97 μm , while Iron bamboo had the shortest at 1,781.20 μm .

Iron bamboo recorded the highest values for fiber diameter, lumen width, and cell wall thickness, averaging 24.20 μm , 7.98 μm , and 7.83 μm , respectively. These were followed by Thailand bamboo, with corresponding averages of 21.48, 7.45, and 6.65 (μm). The lowest values for these fiber features were consistently observed in Solid bamboo. For mechanical properties, Solid bamboo recorded the highest compression strength, averaging 46.16 MPa, followed by Iron bamboo (32.49 MPa) and Thailand bamboo (31.91 MPa), with Yellow bamboo showing the lowest value (31.31 MPa). Conversely, Yellow bamboo exhibited the highest shear strength, with an average of

15.03 MPa, followed by Thailand bamboo (13.56 MPa) and Solid bamboo (9.87 MPa), while Iron bamboo recorded the lowest (5.68 MPa).

Differences in fiber morphology and mechanical properties for node and internode positions among the four selected bamboo species are showed in Figure 8. All species showed some variation in the node and internode portion. In Iron bamboo, for the node samples, fiber diameter, lumen width, and cell wall thickness were generally greater than for internode samples, while internode samples had greater mean values for fiber length and overall mechanical strength.

For Solid bamboo, node samples had greater mean values for fiber diameter and cell wall thickness than internode samples, while internode samples were greater than node samples in fiber length and in compression strength. In Yellow bamboo, node samples generally had higher values in fiber diameter and cell wall thickness than internodes, while internodes showed equal and in some cases, greater shear strength. In Thailand bamboo, node samples had greater mean values in some selected fiber morphological traits than internodes, while for mechanical properties, internodes were equal in some traits, and greater in others. The influence of nodal position is species dependent.

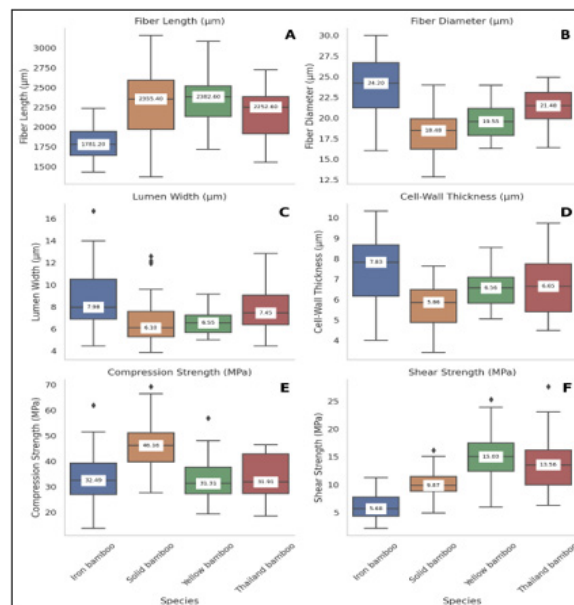


Figure 5 Fiber morphological properties and mechanical properties of four bamboo species

Notes: A = fiber length (μm); B = fiber diameter (μm); C = lumen width (μm); D = cell wall thickness (μm); E = compression strength (MPa); F = shear strength (MPa). Values inside the boxes indicate mean values ($n = 36$ per species).

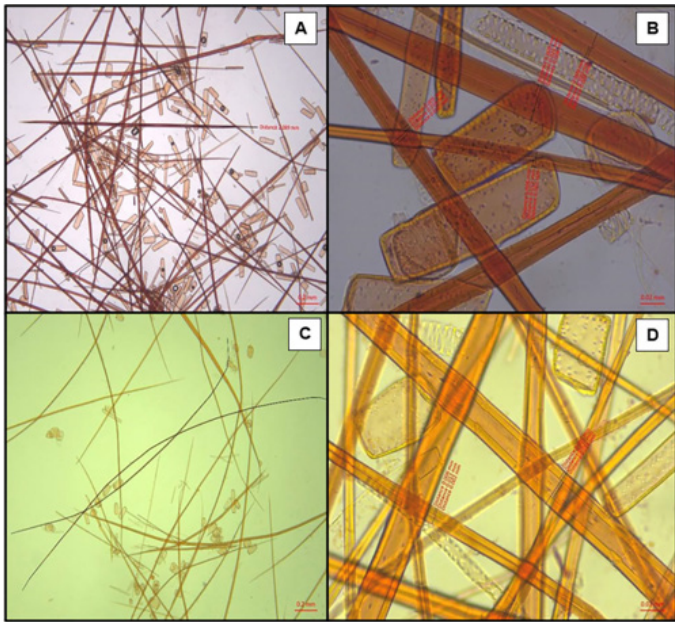


Figure 6 Representative photo of macerated fibers from two bamboo species
Notes: (A–B) Iron bamboo showing (A) fiber length and (B) fiber and lumen diameter; (C–D) Solid bamboo showing (C) fiber length and (D) fiber and lumen diameter.

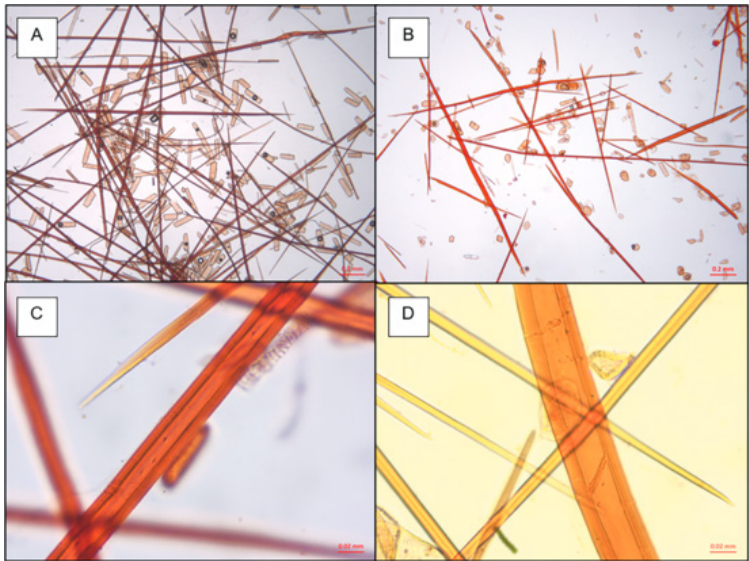


Figure 7 Representative photo of macerated fibers from two bamboo species
Notes: (A–B) Yellow bamboo and Thailand bamboo showing fiber length; (C–D) corresponding images showing fiber and lumen diameter.

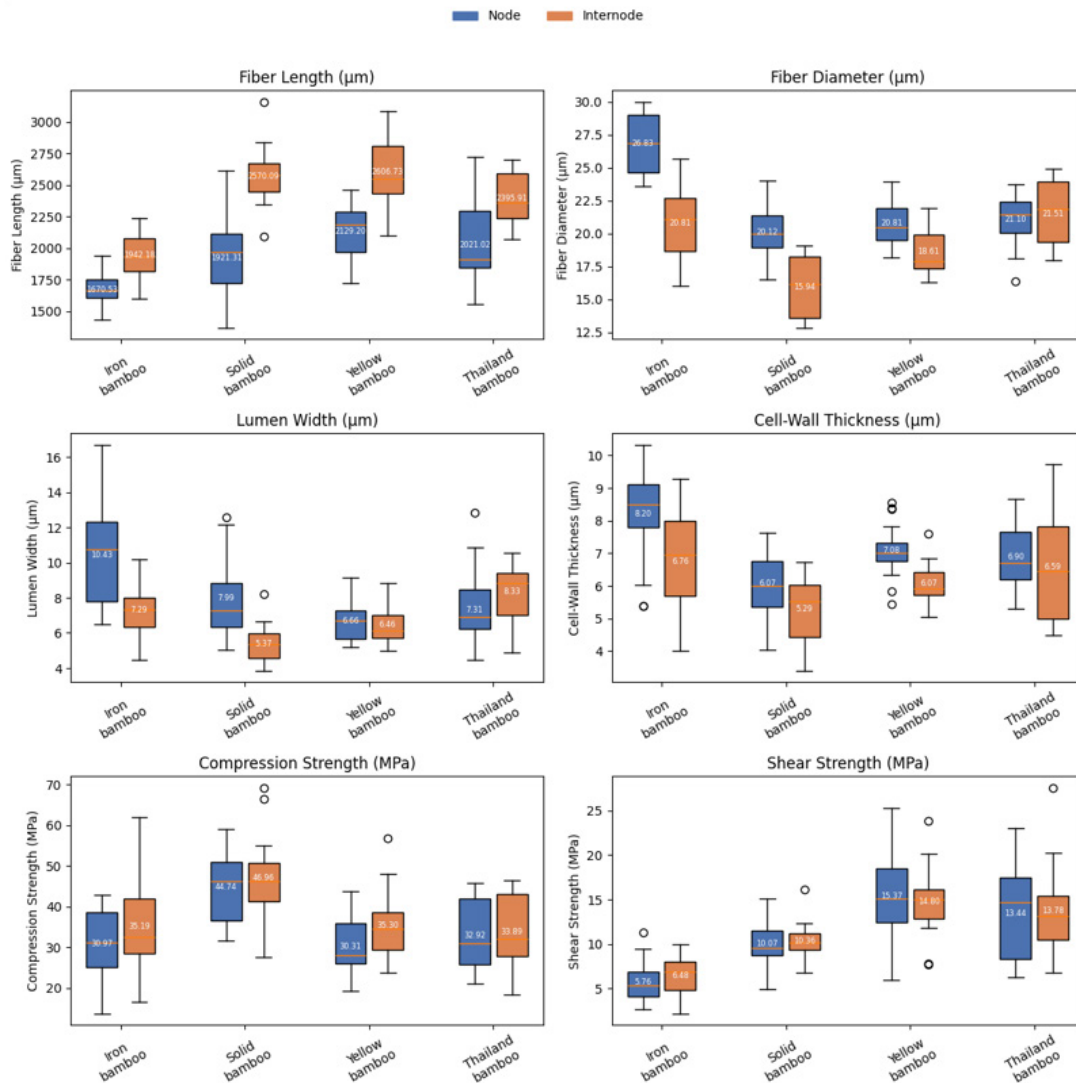


Figure 8 Comparison of fiber morphology and mechanical properties between node and internode portions across four bamboo species

Notes: Values inside the boxes indicate mean values ($n = 18$ per portion per species).

Influence of Fiber Morphology on the Mechanical Properties

Fiber Length

Relationship between the fiber morphology and mechanical properties of the bamboos were shown in Figure 9A and 9B.

Among the four bamboo species, Thailand bamboo exhibited the strongest correlations, with showing a strong positive correlation with shear strength ($r = 0.52$) and a moderate positive correlation with compression strength ($r = 0.34$). This suggests that longer fibers in Thailand bamboo contribute to better load distribution and inter-fiber bonding, enhancing the mechanical performance. Yellow bamboo also showed a weak positive correlation with shear strength (r

$= 0.28$) and a negligible positive correlation with compression strength ($r = 0.06$). Iron bamboo similarly displayed a weak positive association ($r = 0.24$ for shear and $r = 0.17$ for compression).

In contrast, Solid bamboo demonstrated a negligible negative correlation in both shear and compression strength. These findings highlight the species-specific role of fiber length in influencing mechanical performance, with the strongest positive effects observed in Thailand bamboo. Similar patterns were reported by Mohmod *et al.* (1990), who found a positive correlation between fiber length and compression strength in *Bambusa spinosa*, *B. vulgaris* var. *striata*, and *Gigantochloa scortechinii*. A comparable positive relationship was also noted in *B. spinosa* (Espiloy *et al.* 1986), *G. thoi*, *G. ligulata*, and *G. wrayi* (Hamid *et al.* 2023). The

results indicates that the increased fiber length can enhance axial load-bearing capacity by improving fiber-to-fiber bonding and allowing for better distribution of compressive stress throughout the material (Suzuki 1948; Espiloy *et al.* 1986; Zhu *et al.* 2025).

However, Mohmod *et al.* (1990) also reported a negative correlation between fiber length and shear strength, suggesting that while longer fibers may enhance compression resistance, they could also lead to increased vulnerability under transverse or shearing stress. This pattern was

further supported by the findings of Mohmod *et al.* (1993), who similarly found a positive correlation between fiber length and compression strength in *B. spinosa*, alongside a negative correlation with shear strength. These results imply a structural trade-off, where fiber elongation improves axial strength but may weaken the material's ability to resist shear-induced failure (Mohmod *et al.* 1990; Mohmod *et al.* 1993; Marasigan & Daguinod 2025). Conversely, Wahab *et al.* (2018; 2012) documented a weak positive correlation between fiber length and shear strength in *B. vulgaris* and *G. scortechinii*.

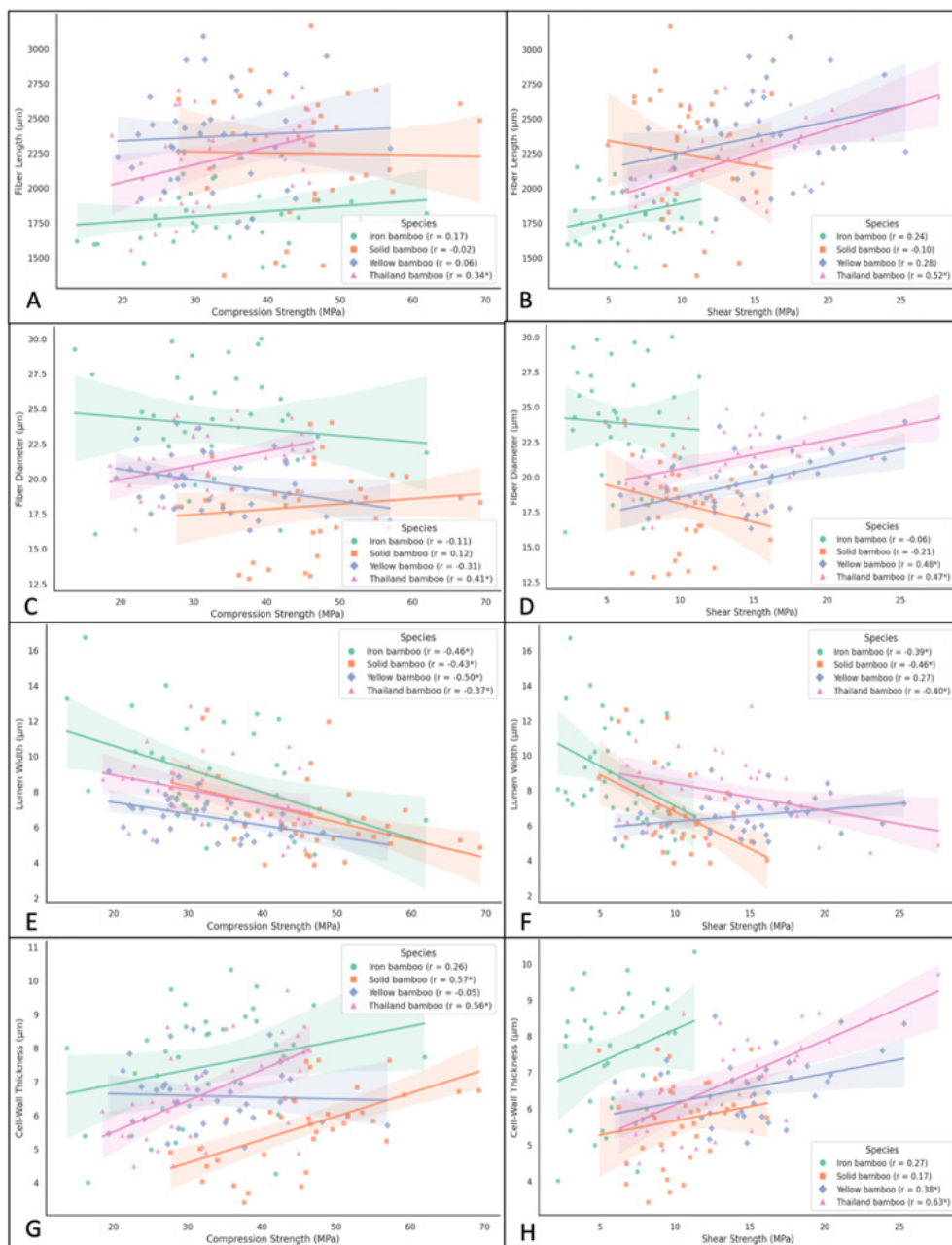


Figure 9 Pearson correlation analysis between fiber morphological properties and mechanical properties of four bamboo species

Notes: $n = 36$ per species. (A–B) Fiber length vs. (A) compression strength and (B) shear strength; (C–D) fiber diameter; (E–F) lumen width; and (G–H) cell wall thickness.

The present results suggest that longer fibers commonly contribute to improved compression and shear strength in Thailand, Yellow, and Iron bamboo, which likely due to enhanced fiber-to-fiber bonding and more efficient stress distribution. In contrast, Solid bamboo exhibits greater mechanical performance with shorter fibers, a behavior consistent with previous findings observed in some Malaysian bamboo species. This indicates that the relationship of fiber length and mechanical properties may vary depending on the anatomical structure and species-specific characteristics of a bamboo (Augustina *et al.* 2025).

Fiber Diameter

The influence of fiber diameter on the mechanical properties of the four bamboo species revealed distinct species-specific trends (Figure 9C and 9D). Thailand bamboo showed significant moderate positive correlations with both compression strength ($r = 0.41$) and shear strength ($r = 0.47$), indicating that larger fiber diameters may enhance structural integrity by improving load distribution and resistance to deformation. Yellow bamboo also exhibited a significant positive correlation with shear strength ($r = 0.48$), while its correlation with compression strength was negative ($r = -0.31$). In contrast, Iron and Solid bamboos displayed weak or inconsistent associations. Iron bamboo showed a negligible weak correlation with both shear ($r = -0.06$) and compression ($r = -0.11$) strength, while Solid bamboo exhibited a weak positive correlation with compression strength ($r = 0.12$) and a negative correlation with shear strength ($r = -0.21$). These findings indicate that the role of fiber diameter in mechanical performance is dependent on species.

In addition to fiber diameter, variations in vascular bundle distribution, fiber proportion, and the structural differences between node and internode regions may also influence mechanical behavior (Darwis *et al.* 2023; Wang *et al.* 2024). These anatomical features affect fiber arrangement and density, which can modify how stresses are distributed within the bamboo culm.

In Thailand bamboo, larger fiber diameters contribute positively to both strength properties. However, Yellow bamboo exhibited a contrasting pattern, showing a positive correlation with shear strength but a negative correlation with compression strength. For Iron and Solid bamboos, the weak correlations indicate that fiber diameter has minimal impact on strength and may be overshadowed by other structural factors.

Similar patterns have been reported in previous studies. Mohmod *et al.* (1990) observed positive correlations between fiber diameter and both strength properties in *B. spinosa*, *B. vulgaris* var. *striata*, and *G. scortechinii*. Likewise, Mohmod *et al.* (1993) and Hamid *et al.* (2023), noted positive associations between fiber diameter and compression strength in *B. spinosa* and *G. wrayi*. On the other hand, Wahab *et al.* (2018; 2012) reported a strong positive correlation between fiber diameter and shear strength in *B. vulgaris* and *G. scortechinii*. In contrast, Espiloy *et al.* (1986) reported a negative correlation between fiber diameter and compression strength in *G. levis*.

Lumen Width

The relationship between lumen width and mechanical strength (Figure 9E and 9F) exhibited a generally negative trend across all species, particularly with respect to compression strength. Yellow bamboo showed the strongest negative correlation ($r = -0.50$), suggesting that narrower lumens enhance axial load-bearing capacity. Similar negative correlations were observed in Iron bamboo ($r = -0.46$), Solid bamboo ($r = -0.43$), and Thailand bamboo ($r = -0.37$), indicating that reduced lumen width resulted to thicker cell walls and higher tissue density that contributes to improved compressive performance.

This trend may also be influenced by other anatomical factors, including vascular bundle distribution and fiber proportion within the culm (Darwis *et al.* 2023; Wang *et al.* 2024).

For shear strength, negative correlations were also observed in Iron bamboo ($r = -0.39$), Solid bamboo ($r = -0.46$), and Thailand bamboo ($r = -0.40$). However, Yellow bamboo deviated from this pattern, exhibiting a weak positive correlation ($r = 0.27$), likely due to species-specific anatomical properties. The findings suggest that narrower lumen widths enhance mechanical performance by reducing void space and increasing structural compactness.

Comparable observations were made by Mohmod *et al.* (1990), who reported a negative correlation between lumen width and compression strength in *B. spinosa*, *B. vulgaris* var. *striata*, and *G. scortechinii*, but a strong positive correlation with shear strength. This suggests that the larger the lumen may compromise the material's ability to resist compressive loads, and may contribute to improved resistance against shearing forces, possibly due to greater flexibility or altered internal

stress distribution within the fiber structure. In contrast, Mohmod *et al.* (1993) found a weak negative correlation between lumen width and shear strength and a weak positive correlation with compression strength in *B. spinosa*. Wahab *et al.* (2018; 2012) further supported the trend of a negative correlation between lumen width and shear strength in *B. vulgaris* and *G. scortechinii*, emphasizing the variable influence of these anatomical traits across species. Additionally, Espiloy *et al.* (1986) reported a negative correlation between lumen width and compression strength in both *B. spinosa* and *G. levis*. Similarly, among the species reviewed by Hamid *et al.* (2023), *Schizostachyum zollingeri*, *B. heterostachya*, and *G. wrayi* also exhibited a negative association between fiber lumen width and compression strength.

Cell Wall Thickness

The relationship between cell wall thickness and mechanical strength (Figure 9G and 9H) showed consistently positive trends across species. Thailand bamboo exhibited the strongest associations, with thicker cell walls correlating significantly with both shear strength ($r = 0.63$) and compression strength ($r = 0.56$), suggesting that increased wall thickness enhances the bamboo's capacity to resist both axial and transverse loads. Solid bamboo displayed a similar pattern, with a strong correlation for compression strength ($r = 0.57$) and a weaker, though still positive, correlation with shear strength ($r = 0.17$). Iron bamboo showed a moderate positive correlation with both compression ($r = 0.26$) and shear strength ($r = 0.27$). In contrast, Yellow bamboo showed a positive correlation with shear strength ($r = 0.38$), but a weak negative correlation with compression strength ($r = -0.05$), indicating a less consistent relationship.

Other anatomical features may also contribute to this behavior, including variations in fiber arrangement and structural differences within the culm (Darwis *et al.* 2023; Wang *et al.* 2024).

Comparable findings have been reported in previous studies. Mohmod *et al.* (1990) observed a strong positive correlation between cell wall thickness and compression strength, but only a negligible correlation with shear strength in three Malaysian bamboo species. Similarly, Mohmod *et al.* (1993) reported strong to moderate correlations between cell wall thickness and both shear and compression strength in *B. spinosa*. Wahab *et al.* (2018; 2012) also found a moderate positive association between cell wall thickness and shear strength in *B. vulgaris*. Likewise, Espiloy *et al.* (1986) reported a positive correlation between cell wall thickness and compression strength in *B. spinosa*, and *G. levis*. Hamid *et al.* (2023) also noted similar trends in *G. thoi*, *G. wrayi* and *Dendrocalamus asper*. This suggests that increased cell wall thickness leads to greater resistance to compressive forces and strengthens the structural stability and load-bearing capacity of bamboo, thereby enhancing its mechanical performance under compression (Iswanto *et al.* 2025; Zhu *et al.* 2025).

Anatomical and Strength Properties Analysis Using PCA

To further explore the multivariate relationships among fiber morphology and mechanical properties (compression and shear strength), Principal Component Analysis (PCA) was performed for each bamboo species (Fig. 10). This approach helps identify key traits contributing to mechanical properties and explains how fiber morphology shapes species-specific strength characteristics.

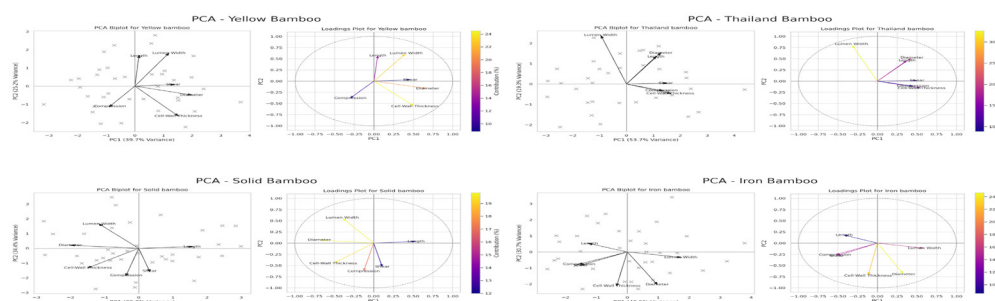


Figure 10 Principal Component Analysis (PCA) of fiber morphology and mechanical properties of four bamboo species

Notes: $n = 36$ per species. (Left) PCA biplots showing sample distribution; (Right) loading plots showing trait contributions. Axis labels indicate the percentage of variance explained by PC1 and PC2.

For Yellow bamboo, PC1 and PC2 accounted for 39.7% and 25.2% of the total variance, respectively. The loadings plot showed that cell wall thickness, fiber diameter, and lumen width contributed the most to PC1, while PC2 captured variance associated more with fiber length and lumen width. Cell wall thickness accounted for most of the variation in PC1, while PC2 primarily reflected differences in fiber length and lumen width. Compression and shear strength vectors closely followed the direction of cell wall thickness, indicating its significant influence on mechanical behavior. In the case of Yellow bamboo, the proximity of strength vectors to cell wall traits suggests that densely packed fibers and thicker walls enhance its structural performance.

In Thailand bamboo, PC1 explained 53.7% of the variance, with PC2 contributing 19.3%. Fiber length, fiber diameter, and cell wall thickness contributed the most to PC1. The alignment of compression and shear strength vectors with these traits confirms the earlier correlation findings, where Thailand bamboo showed significant positive relationships between these features and mechanical strength. Interestingly, lumen width loaded strongly on PC2 in the opposite direction, reinforcing its negative correlation with strength. These patterns suggest that combining fiber robustness and reduced lumen area strongly influences Thailand bamboo's mechanical properties.

For Solid bamboo, PC1 and PC2 accounted for 39.8% and 34.4%, respectively. The PCA revealed that compression and shear strength clustered closely and aligned with cell wall thickness, suggesting a shared structural dependency. Meanwhile, fiber length and lumen width showed weak directional alignment. The relatively lower contribution of fiber morphological traits to PC1 and PC2 reflects the weak correlation observed in this species.

In Iron bamboo, PC1 and PC2 explained 40.5% and 30.7% of the variance, respectively. PCA loading vectors indicated that fiber diameter and cell wall thickness were the most influential on PC1, while PC2 captured the variance associated with fiber length and mechanical properties. Notably, the alignment of compression and shear strength vectors with cell wall thickness indicates a strong structural association among these properties.

The PCA results highlight cell wall thickness as the most significant factor influencing bamboo strength across the species studied. Fiber length

and diameter influence bamboo's mechanical properties. However, their effects vary among species. Aligning these fiber properties with mechanical strength vectors can aid in optimizing the utilization and processing methods for each species. While the sample size captures variation across culms, sections, and positions, the relatively modest replication may limit the generalization of PCA results.

CONCLUSIONS

This study evaluated the fiber morphology and mechanical properties of four bamboo species (Yellow bamboo, Iron bamboo, Solid bamboo, and Thailand bamboo), highlighting the species-specific relationships between fiber traits and strength properties. Thailand bamboo showed the strongest positive correlations, particularly on fiber length, fiber diameter, and cell wall thickness toward compression and shear strength. Yellow bamboo had the longest fibers and highest shear strength, with results indicating that cell wall characteristics contribute significantly to its performance. In contrast, Solid bamboo exhibited the highest compression strength but weaker correlations with fiber morphology. Iron bamboo showed moderate relationships across fiber morphology and strength values. Cell wall thickness consistently appeared as the strongest contributor to mechanical strength among all fiber morphological features. Likewise, lumen width showed a negative association, suggesting that narrower lumens and compact fibers enhance strength properties. These results indicate that strength properties are primarily influenced by cell wall development, with fiber length and diameter contributing to varying extents across species due to inherent anatomical and structural differences.

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