Vol. 15(1): 1-20, January 2027 DOI: https://doi.org/10.23960/jsl.v15i1.1536

P-ISSN: 2339-0913
E-ISSN: 2549-5747

Jurnal Sylva Lestari

Journal homepage: https://sylvalestari.fp.unila.ac.id

Full-Length Research Article

Assessment of Culm Properties of 12 Ornamental Bamboo Taxa Grown in Luzon, Philippines for Their Potential Applications

Oliver Segundo Marasigan*, Mario Angelo Micosa Mundin, Shereyl Aguirre Daguinod, Dundaele Kyle Bayer Melendez, Prince Ranier Cacaos Rana

Forest Products Research and Development Institute (FPRDI), Department of Science and Technology (DOST), College, Laguna, Philippines
* Corresponding author. E-mail address: oliver.marasigan@fprdi.dost.gov.ph

ARTICLE HISTORY:

Received: 21 April 2026
Peer review completed: 30 June 2026
Received in revised form: 5 August 2026
Accepted: 18 August 2026

KEYWORDS:

Bamboo utilization
Density
Mechanical properties
Physical properties
Value-added applications

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ABSTRACT

Ornamental bamboos are widely cultivated for landscaping, but their value-added potential remains underexplored. In this study, 12 ornamental bamboo species from Luzon Island, Philippines, viz. Pink bamboo (*Gigantochloa kuring* Widjaja), Buhong dilaw [*Schizostachyum brachycladum* (Kurz ex Munro) Kurz], Black bamboo (*Gigantochloa atroviolacea* Widjaja), Pole bamboo (*Thyrsostachys siamensis* Gamble), Variegated bamboo [*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f. 'Variegata'], Buddha belly (*Bambusa ventricosa* McClure), Wamin (*Bambusa vulgaris* Schrad. ex J.C.Wendl. 'Wamin'), Taiwan [*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f.], Sunburn [*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f. 'Alphonse Karr'], Vivax (*Phyllostachys vivax* McClure), Chino [*Pleioblastus argenteostriatus* (Regel) Nakai 'Hisauchii'], and Dulcis (*Phyllostachys dulcis* McClure) were evaluated. Six culms per species were tested for physical and mechanical properties following ASTM D143 (2019) and ISO 22157 (2019). Species comparisons used bottom-culm specimens, while axial effects were assessed only in sufficiently long culms. Moisture content (MC), basic relative density (RD), shrinkage, and mechanical properties varied significantly across species. Axial position significantly affected selected physical properties in some species, whereas most mechanical properties showed no significant axial variation, and nodal position had limited influence on compression and shear strength. Taiwan bamboo and Sunburn bamboo had relatively high RD, whereas Wamin bamboo and Buddha belly showed low RD and high MC. MC was negatively correlated with RD and positively correlated with shrinkage, while RD was positively correlated with mechanical properties. Chino bamboo and Sunburn bamboo exhibited high bending strength and stiffness, whereas Vivax and Dulcis bamboo showed high compression strength. Several ornamental species had properties comparable to commercially utilized bamboos. Based on the physical and mechanical properties, selected species show potential for furniture, laminated bamboo products, decorative panels, semi-structural and other specialty products; lower-strength species may suit decorative and non-structural uses. These findings highlight the potential of ornamental bamboo for value-added applications beyond landscaping.

1. Introduction

Because it is a rapidly growing, easily processed raw material, bamboo can be used in everything from furniture and construction to crafts and paper, textiles, and ecological restoration (DOST-PTRI 2021; Siam et al. 2019). In the Philippines, the bamboo species used are no longer limited to their traditional uses. Some have been cultivated for decorative landscaping and other urban greening sectors due to the aesthetic value of their structures and foliage. The Black bamboo (*Gigantochloa atroviolacea* Widjaja), Pole bamboo (*Thyrsostachys siamensis* Gamble), Variegated bamboo [*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f. 'Variegata'], Taiwan bamboo [*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f.], Buhong dilaw [*Schizostachyum brachycladum* (Kurz ex Munro) Kurz], and Vivax bamboo (*Phyllostachys vivax* McClure) are among the bamboos that can be found in some parks and other commercial landscaping (FMB–DENR 2022; Roxas et al. 2000; Roxas 2012).

Most ornamental bamboo species evaluated in this study are exotic species in the Philippines (Opeña et al. 2023; Roxas 2012). They were brought in for ornamental purposes. They have now spread to regional and provincial plantations and public and private landscapes (Roxas 2012). Beyond ornamental use, these bamboo species attract growers and small nursery producers because they can be propagated and sold as a livelihood (Irader 2015). The study evaluated 12 ornamental bamboo species because they are the most commercially available in Luzon, Philippines, where they are frequently used in landscaping, urban greening, and nursery systems (FMB–DENR 2022; Opeña et al. 2023; Roxas et al. 2000; Roxas 2012). Bamboo species that are cultivated for landscaping and urban greening are also used for handicrafts, furniture, construction, pulp and paper, and other bamboo products (Roxas 2012). Information on ornamental bamboo's physical and mechanical properties remains limited, even though these species are readily accessible and have many uses.

Comprehensive data on the area dedicated to cultivating and producing ornamental bamboo species in the Philippines remain limited, yet Roxas (2012) notes their widespread presence in bambusetas, botanical gardens, nurseries, and urban designs. A recent report by Opeña et al. (2023) has classified ornamental bamboo species in the Philippines. Moreover, while most of these species are used for indoor and outdoor landscaping, hedges and ground cover, some species with larger culms are used for handicrafts, musical instruments, furniture, construction, engineered bamboo and its derived products and paper (Roxas 2012).

Recent studies have also shown that several ornamental bamboo species have characteristics suitable for value-added applications beyond landscaping. Tang et al. (2022) reported that *T. siamensis* has favorable processing characteristics for housing, furniture, and other bamboo-based products. Likewise, Sulaiman et al. (2018) found that *S. brachycladum* exhibits desirable anatomical, physical, and mechanical properties suitable for engineered bamboo applications, while Xu and Wang (2023) highlighted the potential of *P. vivax* for engineered bamboo applications. Previous studies have also shown that the physical and mechanical properties of ornamental bamboo vary considerably within and among species. Iswanto et al. (2025) reported that the compression and shear strength of *G. atroviolacea* were significantly influenced by culm height and the presence of nodes. Similarly, Cao et al. (2022) demonstrated that the anatomical characteristics and uneven distribution of vascular tissues in *Pleioblastus argenteostriatus* (Regel) Nakai 'Hisauchii' are associated with variations in its physical and mechanical properties and utilization potential. These studies indicate that ornamental bamboo species possess considerable

potential for applications beyond landscaping. However, comprehensive information on their physical and mechanical properties remains limited, particularly for ornamental bamboo species cultivated in the Philippines, highlighting the need for the present study.

Ornamental bamboo species in the Philippines remain understudied, despite research on ornamental bamboo species having been conducted in various countries. Information on their physical and mechanical properties is limited, including moisture content, density, shrinkage, bending, compression, shear, and variations among species and along the culm. These properties are essential for understanding bamboo behavior and performance and for evaluating whether culms from landscape maintenance and nursery production can be repurposed as raw materials for handicrafts, furniture, construction, and other value-added products rather than discarded. Therefore, this study evaluated the physical and mechanical properties of selected ornamental bamboo species in the Philippines to determine their potential for industrial and value-added applications.

2. Materials and Methods

2.1. Sampling and Culm Preparation

The species selection was based on the identification and distribution of ornamental bamboo species reported by Roxas (2012), which was used as the primary reference for identifying ornamental bamboo species in the Philippines. The selected species were chosen based on their wide distribution and commercial availability in the Philippines. Planting materials were obtained from the Department of Environment and Natural Resources – Ecosystems Research and Development Bureau through its Watershed and Water Resources Research, Development and Extension Center and Los Baños Experimental Station, the Bamboo and Rattan RDE Center of Pampanga State Agricultural University, and the Philippine Bamboo Foundation. All bamboo culms were collected from managed botanical gardens and were approximately 4–5 years old, with culm age determined from plantation and nursery records and verified using the age classification described by Santos (2018). **Table 1** presents the collection sites and culm characteristics, while **Fig. 1** shows the representative culms of the ornamental bamboo species.

For each species, six culms were harvested from six different clumps. All culms were cut at approximately 30 cm above ground level. The total culm height was measured from the base to the culm tip. Culm diameter was determined at the basal internode in the bottom portion of the culm as the average of two perpendicular outside diameter measurements. Culm wall thickness was determined as the average of four measurements taken at 90° intervals around the culm cross-section. Species subjected to axial sampling (**Table 1**) were selected based on sufficient culm length and culm straightness to allow the preparation of standardized test specimens. They were divided into three equal portions: bottom, middle, and top. The length of each portion was determined by dividing the total culm length by 3, yielding segments of equal longitudinal distance along the culm. The sampling scheme used in this study is shown in **Fig. 2**.

Table 1. Collection site and culm characteristics

Assigned letter	Common name	Scientific name	Type of bamboo	Collection site	Culm diameter (mm)	Culm wall thickness (mm)	Culm height (m)
A	Pink bamboo**	*Gigantochloa kuring* Widjaja	Sympodial	Los Baños, Laguna	48.52 ± 5.80	4.00 ± 0.51	8.35 ± 0.82
B	Buhong dilaw**	*Schizostachyum brachycladum* (Kurz ex Munro) Kurz	Sympodial	Los Baños, Laguna	33.9 ± 2.22	4.11 ± 0.42	7.51 ± 0.37
C	Black bamboo**	*Gigantochloa atroviolacea* Widjaja	Sympodial	Los Baños, Laguna	53.59 ± 5.85	4.53 ± 0.48	8.75 ± 0.48
D	Pole bamboo**	*Thyrsostachys siamensis* Gamble	Sympodial	Los Baños, Laguna	44.89 ± 5.60	3.67 ± 0.46	7.80 ± 0.49
E	Variegated bamboo*	*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f. 'Variegata'	Sympodial	Bay, Laguna	14.33 ± 0.54	1.26 ± 0.34	1.50 ± 0.22
F	Buddha belly*	*Bambusa ventricosa* McClure	Sympodial	San Pablo, Laguna	32.69 ± 3.31	3.50 ± 0.43	1.65 ± 0.21
G	Wamin bamboo*	*Bambusa vulgaris* Schrad. ex J.C.Wendl. 'Wamin'	Sympodial	Bacolor, Pampanga	83.27 ± 5.17	6.04 ± 0.46	3.50 ± 0.29
H	Taiwan bamboo**	*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f.	Sympodial	Baguio, Benguet	23.65 ± 3.33	1.95 ± 0.42	4.20 ± 0.32
I	Sunburn*	*Bambusa multiplex* (Lour.) Raeusch. ex Schult.f. 'Alphonse Karr'	Sympodial	San Juan, Batangas	13.76 ± 1.01	1.29 ± 0.27	1.63 ± 0.22
J	Vivax bamboo**	*Phyllostachys vivax* McClure	Monopodial	Baguio, Benguet	44.06 ± 8.92	5.54 ± 0.46	2.10 ± 0.13
K	Chino bamboo**	*Pleioblastus argenteostriatus* (Regel) Nakai 'Hisauchii'	Monopodial	Baguio, Benguet	29.33 ± 2.64	2.37 ± 0.32	3.10 ± 0.23
L	Dulcis bamboo**	*Phyllostachys dulcis* McClure	Monopodial	Baguio, Benguet	53.0 ± 3.04	4.41 ± 0.38	11.30 ± 0.37

Notes: Assigned letters (A–L) correspond to the species codes used in Figures 3 and 5. * = Single-section sampling (bottom only); ** = Axial sampling (bottom, middle, and top).



Fig. 1. Culm photographs of the ornamental bamboo species. a) Black bamboo; b) Buhong dilaw; c) Variegated bamboo; d) Wamin bamboo; e) Taiwan bamboo; f) Pink bamboo; g) Pole bamboo; h) Sunburn; i) Buddha belly; j) Chino bamboo; k) Vivax bamboo; l) Dulcis bamboo.

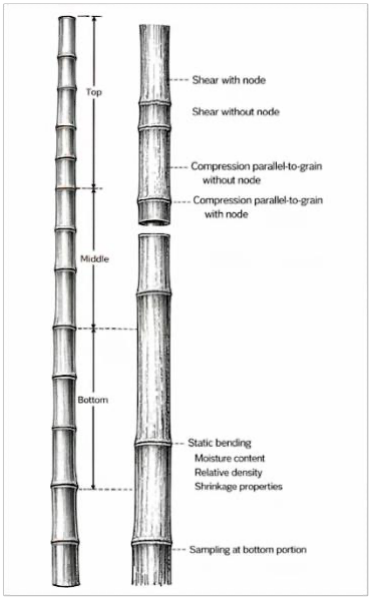


Fig. 2. Sampling scheme for determining the culm properties of ornamental bamboo species, showing the bottom, middle, and top sampling positions used for species with axial classification and the specimen locations for each physical and mechanical test. Species without axial classification were sampled only from the bottom portion.

2.2. Physical Properties

The physical properties of bamboo, including green moisture content (MC), basic relative density (RD), and shrinkage properties, were determined in accordance with ASTM D143 (2019). Although ISO 22157 (2019) provides procedures for determining moisture content and density, it does not include methods for shrinkage determination. Therefore, ASTM D143 (2019) was adopted to provide a standardized and consistent methodology for evaluating all physical properties investigated in this study. The standard specimen dimensions were modified to accommodate the hollow cylindrical geometry and variable culm wall thickness (CWT) of bamboo, while retaining the testing procedures and calculation methods specified in ASTM D143 (2019).

Specimen dimensions are expressed as tangential (T) × radial (R) × longitudinal (L). For each culm, four slat specimens measuring 25 mm (T) × CWT (R) × 125 mm (L) were collected. From each slat, a specimen measuring 25 mm (T) × CWT (R) × 25 mm (L) was prepared for MC and RD determination, while the remaining portion (25 mm [T] × CWT [R] × 100 mm [L]) was used for shrinkage testing. The actual specimen dimensions were measured and used to calculate the physical properties. The outer skin and inner layer were retained, while nodes were excluded from the specimens. The natural curvature of the culm wall was maintained during specimen preparation, and no flattening treatment was applied.

Green MC was determined from the ratio of green to oven-dry mass. Green and oven-dry masses were measured using a Shimadzu UX8200S digital balance (Shimadzu Corp., Japan; ± 0.1 g linearity), and specimens were oven-dried at 103 ± 2°C until constant mass using a Fisher Scientific Isotemp 650G oven (Thermo Fisher Scientific, USA). Green volume was measured using the water displacement method, and RD was calculated as the oven-dry mass divided by the measured green volume. Shrinkage properties were determined as the percentage dimensional

change from the green to oven-dry condition, with specimen dimensions measured using a Mitutoyo ABS AOS digital caliper (Mitutoyo Corp., Japan; 0.0254 mm resolution).

2.3. Mechanical Properties

Mechanical properties were evaluated using a Shimadzu UH-300 kNX Universal Testing Machine (Shimadzu Corp., Japan) in accordance with ASTM D143 (2019) and ISO 22157 (2019). All mechanical tests were conducted on green specimens. Static bending properties were determined using whole-culm specimens subjected to a three-point bending test in accordance with ASTM D143 (2019). Although ISO 22157 (2019) specifies a four-point bending test requiring a minimum specimen length of 30 × the culm outer diameter, this requirement could not be satisfied because most ornamental bamboo species evaluated in this study had relatively short culms. Therefore, a modified three-point bending method based on ASTM D143 (2019) was adopted to determine the stress at the proportional limit (SPL), the modulus of elasticity (MOE), and the modulus of rupture (MOR).

The specimen length was set to 14 times the culm outer diameter at the corresponding sampling position (bottom, middle or top) to maintain the span-to-depth ratio specified in ASTM D143 (2019). For the four species not evaluated by axial position, bending specimens were obtained only from the bottom portion of each culm. Six culms per species, across four species, yielded a total of 24 static bending specimens. For the eight species evaluated by axial position, one bending specimen was obtained from each of the bottom, middle, and top sampling positions of every culm. Thus, six culms per species yielded 18 static bending specimens (144 specimens). Each specimen was supported on two wooden saddle supports, and the load was applied at the midspan at a crosshead speed of 15 mm/min.

Compression (CS) and shear (SS) strengths were determined in accordance with ISO 22157 (2019) using full-round culm specimens with and without nodes. Specimen height (longitudinal dimension) was 10 × CWT, whereas the tangential and radial dimensions corresponded to the natural culm circumference and wall thickness, respectively. Nodes were positioned at the mid-height of the specimen. Equal numbers of nodal and internodal specimens were prepared for each species. The end surfaces were prepared to be flat, parallel to each other, and perpendicular to the specimen's longitudinal axis to ensure uniform load transfer during testing. Compression and shear tests were performed at a crosshead speed of 0.60 mm/min. For the four species not evaluated by axial position, 12 compression specimens and 12 shear specimens were prepared per species from the bottom portion, resulting in 48 specimens per test. For the eight species evaluated at three axial positions (bottom, middle, and top), 36 compression and 36 shear specimens were prepared per species, for a total of 288 specimens per test.

2.4. Statistical Analysis

Normality was assessed using the Kolmogorov–Smirnov test, and homogeneity of variance was assessed using Levene's test. The assumptions of normality and homogeneity of variance were satisfied ($p > 0.05$) prior to ANOVA. A one-way ANOVA was conducted to determine differences among species for each property assessed. In addition, a factorial ANOVA was conducted with the eight species evaluated at three axial levels to determine the effects of axial position (bottom, middle, and top), nodal condition (node versus internode), and their interactions on the physical and mechanical properties assessed.

Mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) to determine whether any means were statistically different from each other. Mean values that shared different letters were considered significantly different. Pearson's correlation was used to assess the strength of relationships among measured properties. Statistical significance was evaluated at $p < 0.05$ for all analyses. All statistical analyses were performed using RStudio software (R Core Team 2022).

3. Results and Discussion

3.1. Variation in Properties Among Species

3.1.1. Physical properties

The analysis showed significant variation among species ($p < 0.05$) in green moisture content (MC) of the bottom portion of ornamental bamboo. The green MC ranged from 16.80% to 220.80% (**Fig. 3a**). The highest MC was recorded in Wamin bamboo, which was followed by Buddha belly and Pole bamboo. In contrast, Sunburn bamboo recorded the lowest MC. For basic relative density (RD), the bottom portion also showed significant differences among species ($p < 0.05$). An inverse pattern was observed in RD: both Taiwan bamboo and Sunburn exhibited the highest values, while Buddha belly and Wamin bamboo showed the lowest RD (**Fig. 3b**).

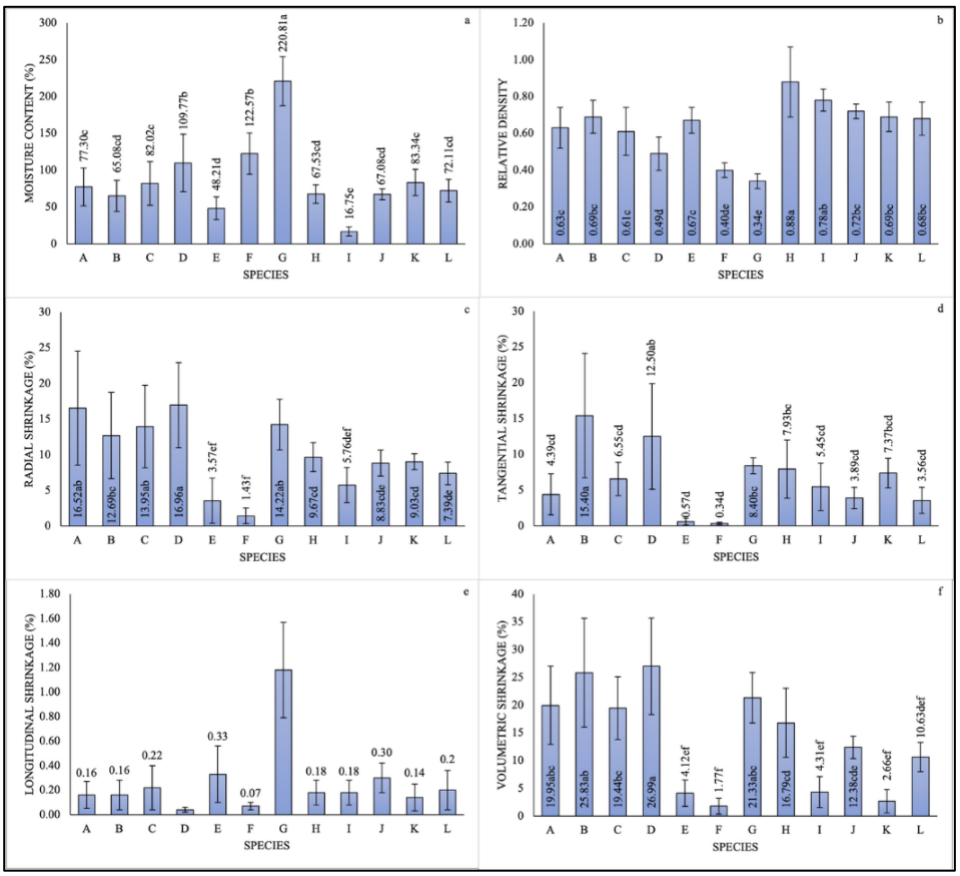


Fig. 3. Physical properties of ornamental bamboo based on specimens obtained from the bottom portion of the culm. a) Moisture content, b) Relative density, c) Radial shrinkage, d) Tangential shrinkage, e) Longitudinal shrinkage, and f) Volumetric shrinkage. Bars represent the mean ± standard deviation (n = 24 per species). Different letters above the bars indicate significant differences ($p < 0.05$). Letters (A–L) correspond to the bamboo species listed in **Table 1**.

A negative correlation was observed between MC and RD (r = −0.82) (**Fig. 4**). This indicates that species with the highest MC mostly displayed lower RD, and vice versa. This association was evident in species such as Wamin bamboo, which displayed the highest MC (220.80%) and the lowest RD (0.34), and Buddha belly, which displayed an MC of 122.60% and an RD of 0.40. In contrast, Sunburn showed the lowest MC (16.80%) and a relatively high RD (**Fig. 3**).

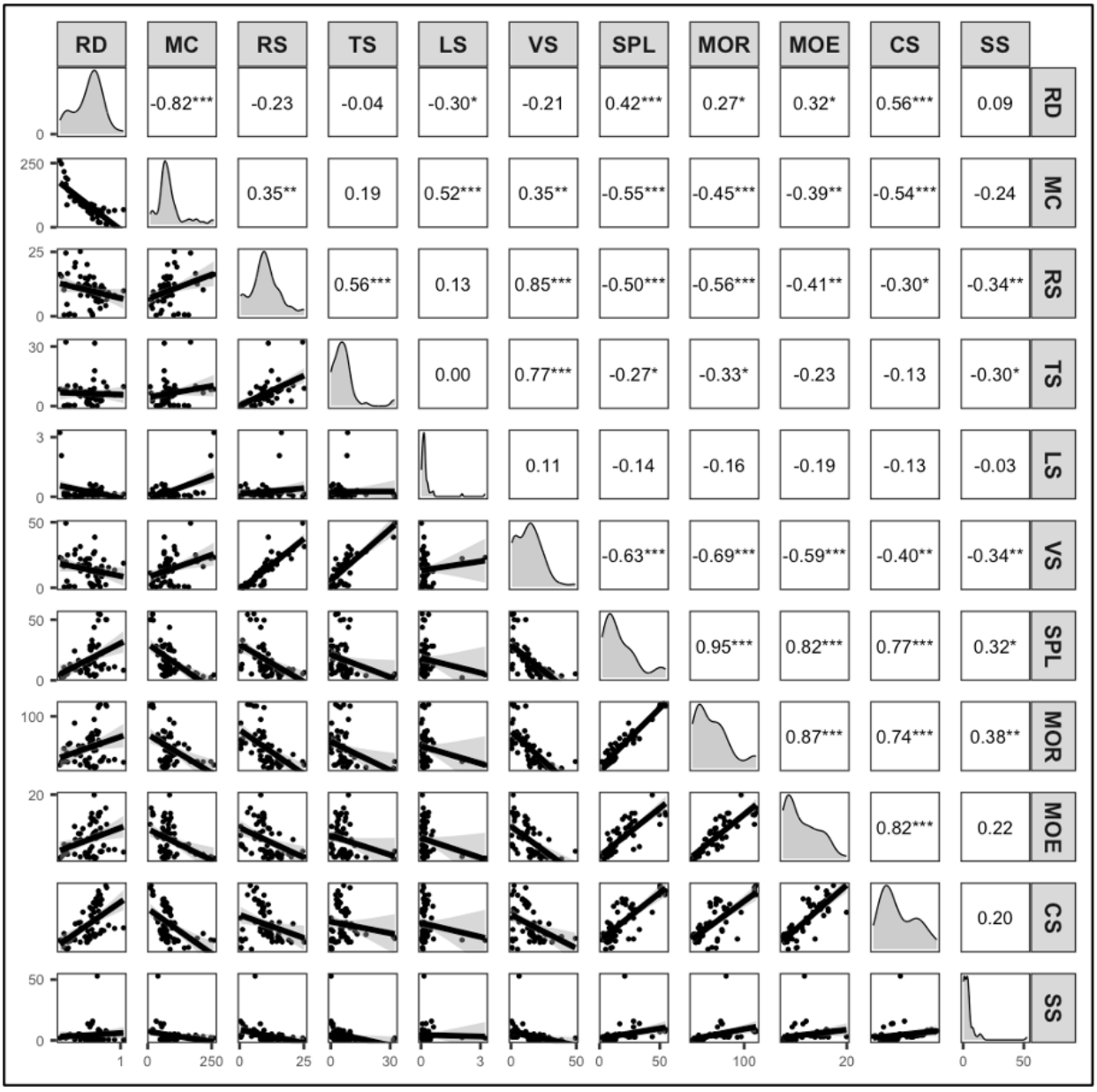


Fig. 4. Pearson correlation matrix of the physical and mechanical properties of ornamental bamboo species based on individual specimen measurements (n = 60). RD = Relative density; MC = Moisture content; RS = Radial shrinkage; TS = Tangential shrinkage; LS = Longitudinal shrinkage; VS = Volumetric shrinkage; SPL = Stress at proportional limit; MOR = Modulus of rupture; MOE = Modulus of elasticity; CS = Compression strength; SS = Shear strength. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

These differences in MC and RD may be associated with variations in morphological and anatomical characteristics. Previous studies have reported that MC is positively associated with cell wall thickness and negatively associated with vascular bundle frequency and lumen diameter

(Villareal et al. 2020). In the present study, Wamin bamboo, which exhibited the highest MC, also had the thickest culm wall. In contrast, Sunburn and Taiwan bamboo, which showed lower MC, had relatively thinner culm walls. Similarly, the higher RD observed in Taiwan bamboo and Sunburn is consistent with previous reports linking thinner culm walls to a higher proportion of vascular bundles with dense fibers (Putri et al. 2023; Villareal et al. 2020). However, anatomical features such as parenchyma proportion and vascular bundle characteristics were not quantified in the present study; thus, direct relationships between these properties and MC and RD were not established.

For shrinkage properties, ANOVA of the bottom portion showed significant variation among bamboo species ($p < 0.05$) (**Fig. 3**). The highest radial shrinkage (RS) was observed in Pole bamboo and Pink bamboo. By contrast, Buhong dilaw and Pole bamboo showed the highest tangential shrinkage (TS). In both RS and TS, Variegated bamboo and Buddha belly recorded the lowest shrinkage (**Fig. 3c and 3d**). For longitudinal shrinkage (LS), Buddha belly showed a significantly higher value than the other bamboo species (**Fig. 3e**). For volumetric shrinkage (VS), Pole bamboo, Buhong dilaw, Wamin and Pink bamboo showed the highest VS values. In contrast, Chino bamboo and Buddha belly displayed the lowest VS (**Fig. 3f**).

RS, VS, and MC showed a positive correlation ($p < 0.01$) (**Fig. 4**). LS showed a significant positive correlation with MC ($p < 0.001$) and a significant negative correlation with RD ($p < 0.05$). This association was reflected across the evaluated species; for instance, Pole bamboo and Buhong dilaw showed higher shrinkage, higher MC and lower RD, whereas Buddha belly and Variegated bamboo showed lower shrinkage, lower MC and higher RD.

The results of the present study were consistent with previous studies reporting positive and negative correlations between shrinkage properties, MC and RD (Awotwe-Mensah et al. 2023; Villareal et al. 2020; Yuan et al. 2023; Zhu and Yang 2025). Previous studies have suggested that higher density may be associated with reduced dimensional changes, whereas a higher proportion of parenchyma cells may contribute to greater shrinkage (Caicedo et al. 2025; Putri et al. 2023; Siam et al. 2019). However, these explanations should be regarded as possible interpretations rather than direct evidence.

The physical properties evaluated in this study are important because they influence dimensional stability, drying behavior, and processing performance, which affect suitability for different applications. The RD of the ornamental bamboo species observed in the present study (0.34 – 0.68) was within the range reported for monopodial and sympodial bamboo species (0.36 – 0.91), while the VS (5.40% – 26.46%) was comparable with values reported for numerous bamboo species (9.60% – 32.80%) (Hamid et al. 2023). Likewise, the RD and directional shrinkage values fell within the ranges reported by Siam et al. (2019) for 13 bamboo species (RD: 0.35–0.75; RS: 3.82%–18.67%; TS: 1.09%–11.45%; and LS: 0.01%–2.95%).

However, this study did not evaluate anatomical characteristics such as vascular bundle distribution, fiber concentration, parenchyma proportion, and lumen diameter. Therefore, the anatomical interpretation discussed above is based on findings from previous studies and should be regarded as possible explanations rather than direct evidence. Future studies integrating anatomical, physical, and mechanical characterization are recommended to verify these relationships.

3.1.2. Mechanical properties

The bottom-portion analysis showed that the modulus of elasticity (MOE), modulus of rupture (MOR), and stress at proportional limit (SPL) differed significantly among species ($p < 0.05$) (**Fig. 5**). Chino bamboo displayed high MOE (15.04 GPa), MOR (72.79 MPa), and SPL (30.83 MPa). In contrast, Sunburn showed the highest MOR (118.98 MPa) and SPL (51.83 MPa). Buhong dilaw and Wamin bamboo consistently showed the lowest bending properties.

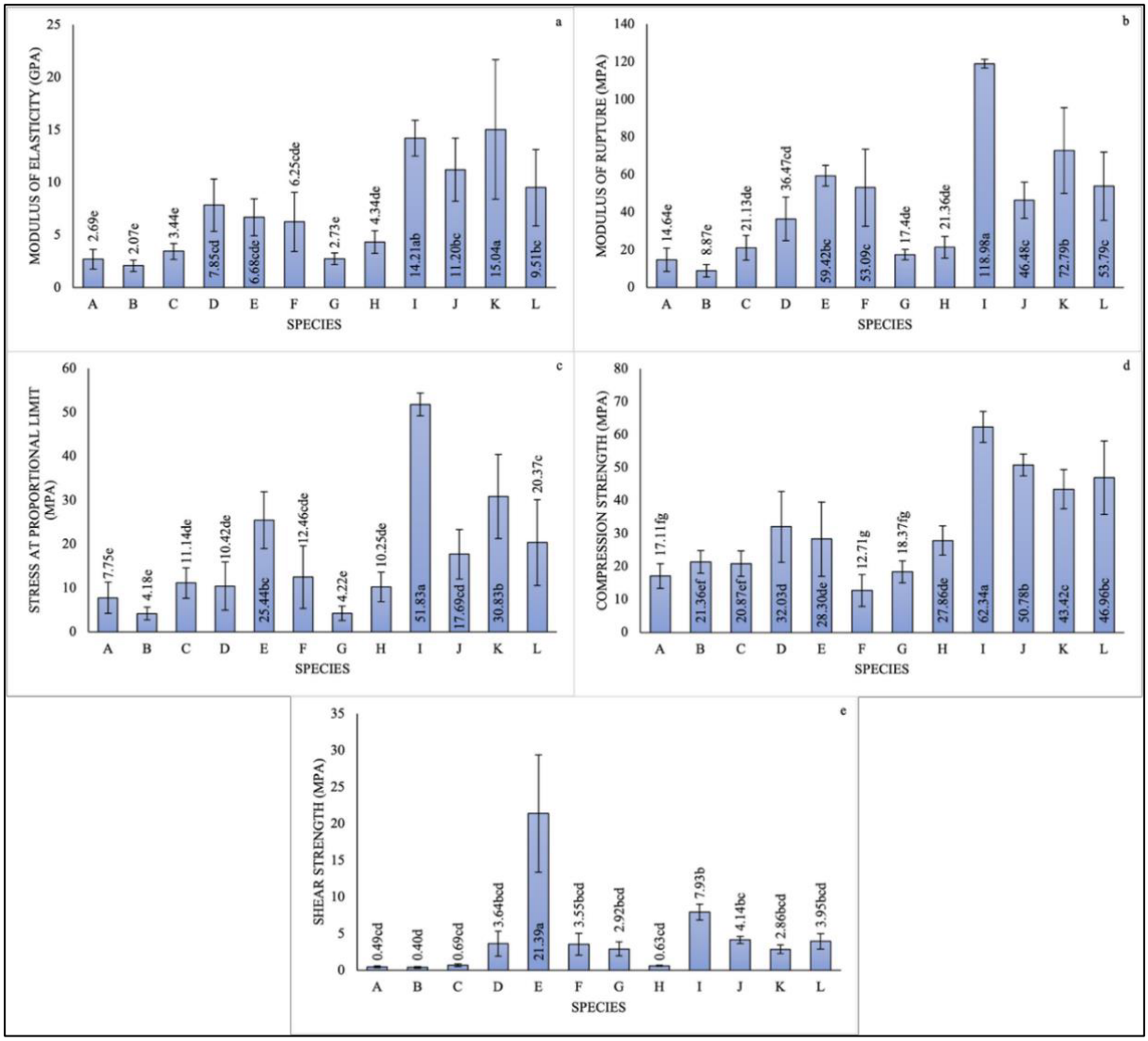


Fig. 5. Mechanical properties of selected ornamental bamboo species based on specimens obtained from the bottom portion of the culm. a) Modulus of elasticity (GPa), b) Modulus of rupture (MPa), c) Stress at proportional limit (MPa), d) Compression strength (MPa), and e) Shear strength (MPa). Bars represent the mean ± standard deviation. Sample sizes were n = 6 per species for static bending properties (a–c) and n = 12 per species for compression and shear strength (d–e). Different letters above the bars indicate significant differences ($p < 0.05$). Letters (A–L) correspond to the bamboo species listed in **Table 1**.

A positive correlation between RD and bamboo bending properties was observed (**Fig. 4**). The results show that species with higher RD exhibited higher static bending. For instance, Sunburn and Taiwan bamboo displayed high RD and bending properties. In contrast, Wamin

bamboo showed lower RD and bending properties. These observed relationships between RD and bending properties are consistent with previously reported findings. Differences in bending properties among species have been reported to correlate with variations in structural characteristics, such as culm diameter and density. Chaydarreh et al. (2025) observed that small culm diameter was associated with higher MOR and bending capacity, while strength decreased as diameter increased. Previous studies have also suggested that anatomical characteristics, including fiber concentration, may influence bending properties (Javadian et al. 2019; Nugroho et al. 2021). However, the present study did not evaluate these anatomical properties and presents them only as possible explanations.

Compression strength (CS) and shear strength (SS) differed significantly among species based on specimens from the bottom portion of the culm ($p < 0.05$). (**Fig. 5d** and **5e**). Sunburn had the highest CS (62.34 MPa). Variegated bamboo had the highest SS (21.39 MPa), followed by Sunburn (7.93 MPa), Vivax bamboo (4.14 MPa), Dulcis bamboo (3.95 MPa), Pole bamboo (3.64 MPa), and Buddha belly (3.55 MPa). Meanwhile, the lowest SS was recorded for Buhong dilaw (0.40 MPa), Pink bamboo (0.49 MPa), and Taiwan bamboo (0.63 MPa). CS and RD were positively correlated ($p < 0.001$) (**Fig. 4**). This relationship was consistent across the evaluated species, with Sunburn exhibiting relatively high RD and CS. In contrast, Buddha belly and Wamin bamboo exhibited lower RD and correspondingly lower CS. No significant correlation was observed between SS and RD.

The mechanical properties obtained in the present study were generally comparable with those reported for commercial bamboo species. Based on Siam et al. (2019) for 13 commercial bamboo species, they reported MOR values ranging from 102 to 263 MPa and MOE values ranging from 9.70 to 21.10 GPa. In the present study, the MOR ranged from 8.87 to 118.98 MPa, and MOE ranged from 2.07 to 15.04 GPa. Likewise, the CS values obtained in this study (12.71–62.34 MPa) were comparable with those summarized by Hamid et al. (2023) for commercially utilized bamboo species. Although several ornamental bamboo species exhibited mechanical properties comparable to commercial bamboo species, many species showed lower bending and CS properties. This difference is expected because ornamental bamboo species generally have smaller culm diameters and thinner culm walls than commercial bamboo species.

Previous studies have reported variations in mechanical properties among species, associated with differences in density and culm characteristics. Studies on Malaysian bamboo species (Siam et al. 2019) and selected species such as *Dendrocalamus latiflorus*, *D. merrillianus*, and *B. vulgaris* (Acma 2017) have documented positive relationships between density and mechanical properties, including CS and SS. Similarly, *G. angustifolia* has been reported to exhibit higher culm strength with higher density (Acosta et al. 2021), while studies on sympodial bamboos (*Gigantochloa* and *Dendrocalamus*) have demonstrated a strong relationship between density and CS (Bahtiar et al. 2019). Hariz et al. (2021) also observed a similar association between density and mechanical properties of *D. asper* and *B. vulgaris*. These previously reported relationships are consistent with the density variation observed in the present study.

The ANOVA results indicated that the effect of nodal condition on the CS and SS of the bottom portion was species-dependent, as shown by the significant interaction between species and nodal condition (**Table 2**). For CS, significant differences between node and internode conditions were observed only in selected species. Taiwan and Variegated bamboo showed significantly lower CS at the node than at the internode, whereas the remaining species did not differ significantly. Regarding SS, significant differences in nodal conditions were observed across

several species. Black bamboo, Pink bamboo, Taiwan bamboo, Vivax bamboo, and Buhong dilaw showed significantly higher SS at the node than at the internode.

Table 2. Comparison of compression and shear strength between the node and internode sections of the bottom portion of selected ornamental bamboo species

Species	Compression Strength (MPa)		Shear Strength (MPa)	
	Internode	Node	Internode	Node
Pink bamboo	$17.28^{a} \pm 2.88$	$16.94^{a} \pm 4.52$	$0.41^{b} \pm 0.12$	$0.56^{a} \pm 0.10$
Buhong dilaw	$20.76^{a} \pm 3.23$	$21.95^{a} \pm 3.54$	$0.32^{b} \pm 0.08$	$0.47^{a} \pm 0.08$
Black bamboo	$21.05^{a} \pm 4.72$	$20.70^{a} \pm 2.88$	$0.60^{b} \pm 0.14$	$0.78^{a} \pm 0.16$
Pole bamboo	$33.05^{a} \pm 9.27$	$31.00^{a} \pm 12.34$	$3.53^{a} \pm 1.51$	$3.74^{a} \pm 1.92$
Variegated bamboo	$35.55^{a} \pm 6.88$	$21.04^{b} \pm 10.36$	$28.75^{a} \pm 2.34$	$14.03^{a} \pm 3.11$
Buddha belly	$14.37^{a} \pm 4.58$	$11.04^{a} \pm 4.97$	$4.01^{a} \pm 2.01$	$3.09^{a} \pm 0.68$
Wamin bamboo	$17.99^{a} \pm 4.47$	$18.76^{a} \pm 2.21$	$2.88^{a} \pm 1.16$	$2.97^{a} \pm 0.84$
Taiwan bamboo	$30.35^{a} \pm 3.46$	$25.36^{b} \pm 3.94$	$0.59^{b} \pm 0.06$	$0.68^{a} \pm 0.09$
Sunburn	$63.69^{a} \pm 3.90$	$60.99^{a} \pm 5.36$	$7.36^{a} \pm 0.41$	$8.49^{a} \pm 1.27$
Vivax bamboo	$51.83^{a} \pm 3.72$	$49.73^{a} \pm 2.65$	$3.96^{b} \pm 0.46$	$4.33^{a} \pm 0.43$
Chino bamboo	$45.46^{a} \pm 5.49$	$41.38^{a} \pm 5.90$	$2.69^{a} \pm 0.68$	$3.03^{a} \pm 0.44$
Dulcis bamboo	$49.30^{a} \pm 10.85$	$44.61^{a} \pm 11.22$	$3.73^{a} \pm 0.91$	$4.18^{a} \pm 1.19$

Notes: Values are presented as mean ± standard deviation (n = 6 per species per nodal condition). Within each row of compression strength and shear strength, means with different superscript letters indicate significant differences between the node and internode sections of the same bamboo species ($p < 0.05$).

Differences between node and internode sections in bamboo have been documented in previous studies. Studies on *Phyllostachys pubescens* and *Bambusa rigida* have reported structural and anatomical differences between node and internode regions, including variations in vascular bundle arrangement and fiber characteristics associated with CS differences (Huang et al. 2018; Putri et al. 2023). Previous research on both erect and clumping bamboo species has also reported higher CS in internode sections (Jimenez et al. 2021).

Variation in SS between the specimen's node and internode regions has also been reported across several bamboo species. Studies on *Gigantochloa apus*, *Bambusa philippinensis*, *B. vulgaris*, *B. spinosa*, and *G. atroviolacea* have reported higher SS in internode regions, whereas higher values in node samples have also been observed in *Dendrocalamus asper* (Bautista et al. 2021; Iswanto et al. 2025; Salzer et al. 2018). These findings indicate that the effect of nodal condition on SS varies among species. The results of the present study, which showed higher SS in node samples for selected species, are consistent with the pattern reported for *D. asper*. However, anatomical characteristics were not quantified in this study, and direct relationships between structure and mechanical properties were not evaluated.

3.2. Effect of Axial Position on Culm Properties

The effect of axial position on the physical and mechanical properties of selected bamboo species was evaluated. It should be noted that not all species had sufficient culm length to be sectioned into three distinct portions; therefore, only species with adequate culm length were included in this analysis. Factorial ANOVA revealed significant effects of axial position and species × axial position interactions for MC, RD, RS, TS, and VS ($p < 0.05$), indicating that axial position influenced these properties differently among species. In contrast, axial position and its interaction with species did not significantly affect the other properties. Consequently, Tukey's

HSD test was used to compare the bottom, middle, and top portions within each species (**Table 3**).

For MC, Black bamboo, Chino bamboo, Pink bamboo, Pole bamboo, Taiwan bamboo, and Buhong dilaw showed significant differences along culm height, with significantly lower MC in the top portion than in the bottom. In contrast, Dulcis bamboo and Vivax bamboo showed no significant variation along the culm height. For RD, an increasing trend toward the top portion was documented across species. However, significant increases occurred only in Chino bamboo, Pole bamboo, Pink bamboo, and Buhong dilaw. Previous studies also observed lower MC and higher density in the upper portion of the bamboo (Adam and Jusoh 2019; Huang et al. 2018; Zakikhani et al. 2017). According to Huang et al. (2018), this can be attributed to differences in tissue distribution (i.e., vascular bundles and parenchyma) along the culm.

The effect of axial position on directional shrinkage was not significant for LS ($p > 0.05$) (**Table 3**). In contrast, axial position showed significant differences for RS in Taiwan bamboo, Chino bamboo, Buhong dilaw, Black bamboo, and Pink bamboo, with generally lower RS values toward the top portion of the culm. TS was significantly affected by axial position in selected species. Black bamboo, Dulcis bamboo, Pink bamboo, Vivax bamboo, and Buhong dilaw showed significantly lower TS values in the top portion than in the bottom and middle portions.

For VS, significant differences in culm height were observed among Buhong dilaw, Black bamboo, Pink bamboo, and Chino bamboo (**Table 3**). Buhong dilaw, Black bamboo, and Pink bamboo generally showed lower VS values in the top portion of the culm, whereas Chino bamboo showed lower VS values in the middle portion.

The differences observed in TS, RS, and VS in this study were consistent with previously reported trends in bamboo, where shrinkage decreases toward the top portion (Siam et al. 2019; Villareal et al. 2020). Zakikhani et al. (2017) and Huang et al. (2018) reported that differences in bamboo shrinkage along the culm were associated with differences in MC, RD, and tissue distribution (i.e., parenchyma and fibers). In addition, Salzer et al. (2018) and Villareal et al. (2020) reported that the variation in culm wall thickness along the culm has been associated with differences in shrinkage properties.

No significant differences among the bottom, middle, and top portions were observed for MOE, MOR, CS, and SS within the evaluated species (**Table 3**). In contrast, SPL varied significantly only in Taiwan bamboo, with the middle portion exhibiting a lower value than the bottom and top portions. Although previous studies have reported higher strength properties in the lower portion of the culm, this trend was not consistently observed in the present study, where most species did not show significant axial differences in mechanical properties. For instance, the bottom portion of bamboo culms from various species showed the highest strength values, with strength decreasing toward the top (Handana et al. 2023). On the other hand, Liu et al. (2021) observed that high variation in bending properties has been documented in other bamboo species. Chaowana et al. (2021) and Nugroho et al. (2021) also linked culm diameter and wall thickness to static bending properties. These reported patterns were not consistently observed in the present study (**Table 3**).

Table 3. Physical and mechanical properties of selected bamboo species at different axial positions

Species	Axial Position	Physical Properties						Mechanical Properties				
		MC (%)	RD	RS (%)	TS (%)	LS (%)	VS (%)	MOE (GPa)	MOR (MPa)	SPL (MPa)	CS (MPa)	SS (MPa)
Taiwan bamboo	Bottom	72.27^{a}	0.78^{a}	11.01^{a}	10.21^{a}	0.30^{a}	20.02^{a}	4.35^{a}	23.52^{a}	11.13^{a}	27.27^{a}	0.64^{a}
	Middle	74.45^{a}	0.88^{a}	9.60^{ab}	5.66^{a}	0.16^{a}	14.68^{a}	3.55^{a}	16.08^{a}	6.98^{b}	28.00^{a}	0.63^{a}
	Top	55.86^{b}	0.98^{a}	8.39^{b}	7.93^{a}	0.09^{a}	15.68^{a}	5.11^{a}	24.48^{a}	12.64^{a}	28.30^{a}	0.63^{a}
Chino bamboo	Bottom	99.38^{a}	0.62^{b}	10.22^{a}	6.67^{a}	0.13^{a}	4.21^{a}	12.44^{a}	66.43^{a}	23.46^{a}	42.31^{a}	3.11^{a}
	Middle	82.74^{ab}	0.67^{b}	8.40^{b}	9.07^{a}	0.15^{a}	1.11^{b}	14.55^{a}	66.02^{a}	27.46^{a}	42.55^{a}	2.76^{a}
	Top	67.89^{b}	0.77^{a}	8.47^{b}	6.36^{a}	0.11^{a}	2.65^{ab}	18.13^{a}	85.91^{a}	41.56^{a}	45.40^{a}	2.71^{a}
Buhong dilaw	Bottom	82.60^{a}	0.61^{b}	18.23^{a}	21.32^{a}	0.14^{a}	35.58^{a}	2.70^{a}	12.86^{a}	5.76^{a}	20.63^{a}	0.41^{a}
	Middle	66.08^{ab}	0.71^{a}	13.43^{b}	20.33^{a}	0.12^{a}	31.16^{a}	1.83^{a}	6.93^{a}	3.04^{a}	21.82^{a}	0.39^{a}
	Top	46.56^{b}	0.75^{a}	6.42^{c}	4.56^{b}	0.19^{a}	10.74^{b}	1.69^{a}	6.82^{a}	3.75^{a}	21.62^{a}	0.40^{a}
Black bamboo	Bottom	97.70^{a}	0.55^{a}	18.03^{a}	8.89^{a}	0.32^{a}	25.30^{a}	4.19^{a}	28.96^{a}	15.20^{a}	20.14^{a}	0.77^{a}
	Middle	84.55^{ab}	0.61^{a}	15.44^{a}	6.64^{a}	0.21^{a}	21.00^{a}	3.05^{a}	17.16^{a}	9.00^{a}	20.05^{a}	0.54^{a}
	Top	63.81^{b}	0.68^{a}	8.37^{b}	4.11^{b}	0.13^{a}	12.03^{b}	3.07^{a}	17.26^{a}	9.24^{a}	22.43^{a}	0.75^{a}
Dulcis bamboo	Bottom	71.95^{a}	0.67^{a}	7.61^{a}	4.80^{a}	0.19^{a}	12.03^{a}	11.34^{a}	65.25^{a}	24.31^{a}	50.18^{a}	4.40^{a}
	Middle	72.77^{a}	0.66^{a}	7.18^{a}	4.36^{a}	0.21^{a}	11.21^{a}	8.78^{a}	49.71^{a}	19.22^{a}	44.39^{a}	3.90^{a}
	Top	71.61^{a}	0.70^{a}	7.37^{a}	1.63^{b}	0.18^{a}	8.63^{a}	8.41^{a}	46.41^{a}	17.58^{a}	46.30^{a}	3.56^{a}
Pole bamboo	Bottom	131.37^{a}	0.44^{b}	19.05^{a}	10.12^{a}	0.03^{a}	27.02^{a}	7.42^{a}	39.21^{a}	12.92^{a}	30.67^{a}	3.51^{a}
	Middle	113.52^{ab}	0.47^{ab}	17.00^{a}	13.24^{a}	0.03^{a}	27.32^{a}	7.82^{a}	33.15^{a}	8.50^{a}	33.55^{a}	3.74^{a}
	Top	84.43^{b}	0.56^{a}	14.83^{a}	14.14^{a}	0.04^{a}	26.61^{a}	8.30^{a}	37.06^{a}	9.85^{a}	31.86^{a}	3.67^{a}
Pink bamboo	Bottom	97.73^{a}	0.54^{b}	21.50^{a}	7.22^{a}	0.00^{a}	26.93^{a}	3.45^{a}	21.76^{a}	11.57^{a}	17.45^{a}	0.60^{a}
	Middle	71.93^{b}	0.66^{a}	17.01^{ab}	4.77^{ab}	0.29^{a}	20.33^{ab}	2.45^{a}	11.16^{a}	6.27^{a}	16.32^{a}	0.45^{a}
	Top	62.23^{b}	0.68^{a}	11.04^{b}	1.78^{b}	0.00^{a}	12.59^{b}	2.19^{a}	10.99^{a}	5.42^{a}	17.56^{a}	0.42^{a}
Vivax bamboo	Bottom	71.20^{a}	0.71^{a}	8.88^{a}	5.05^{a}	0.20^{a}	13.49^{a}	10.84^{a}	51.66^{a}	21.26^{a}	51.71^{a}	4.37^{a}
	Middle	66.34^{a}	0.72^{a}	8.78^{a}	4.37^{a}	0.41^{a}	12.77^{a}	11.28^{a}	43.29^{a}	14.56^{a}	51.58^{a}	4.09^{a}
	Top	63.69^{a}	0.73^{a}	8.82^{a}	2.25^{b}	0.28^{a}	10.87^{a}	11.47^{a}	44.48^{a}	17.25^{a}	49.05^{a}	3.96^{a}

Notes: MC = Moisture content; RD = Relative density; RS = Radial shrinkage; TS = Tangential shrinkage; LS = Longitudinal shrinkage; VS = Volumetric shrinkage; MOE = Modulus of elasticity; MOR = Modulus of rupture; SPL = Stress at proportional limit; CS = Compression strength; SS = Shear strength. Sample sizes were n = 24 per species per axial position for physical properties, n = 6 per species per axial position for static bending properties (MOE, MOR, and SPL), and n = 12 per species per axial position for compression and shear strength. Different letters within the same column and species indicate significant differences among axial positions (bottom, middle, top) at $p < 0.05$.

3.3. Potential Utilization of the Ornamental Bamboo

The physical and mechanical properties obtained in this study are comparable with those reported for commercially used bamboo species. Siam et al. (2019) evaluated the physical and mechanical properties of 13 commercially important bamboo species and identified their potential utilization based on these properties. Several ornamental bamboo species evaluated in the present study exhibited comparable properties, suggesting their potential for similar value-added applications. Based on these properties, Siam et al. (2019) identified potential uses for these species in furniture, handicrafts, basketry, blinds, decorative products, and, for higher-strength species, structural and engineered bamboo applications. Likewise, Hamid et al. (2023) emphasized that higher-density, higher-strength bamboo species are generally preferred for structural products, furniture, flooring, and engineered bamboo products. In contrast, lower-density, lower-strength species are more suitable for handicrafts, basketry, decorative products, blinds, and other light-duty applications. Accordingly, several ornamental bamboo species evaluated in the present study may also have potential for similar applications, subject to their relatively small culm diameter, thinner culm walls, and other morphological limitations.

Species that exhibited relatively high RD, MOE, MOR, and CS, such as Chino bamboo, Vivax bamboo, Dulcis bamboo, and Sunburn, may have potential for high-value applications including furniture components, decorative panels, laminated bamboo products, and other specialty products, as these properties are comparable to those reported for commercially utilized bamboo species such as *B. vulgaris*, *Gigantochloa scortechinii*, and *D. asper*, which have been recommended for similar applications (Siam et al. 2019).

Nevertheless, Natividad and Jimenez (2015) demonstrated the successful use of *Schizostachyum lumampao*, a small-diameter bamboo species, for engineered bamboo products, suggesting that ornamental bamboo species with favorable properties may also have potential for similar value-added products after appropriate processing and product development.

Furthermore, Black bamboo, Pink bamboo, Pole bamboo, and Buhong dilaw may suit furniture and semi-structural applications. In round form, these species may have potential for use in frames and decorative applications. They may also serve as raw materials for engineered bamboo products.

Species with relatively lower relative density and mechanical properties, such as Wamin bamboo and Buddha belly, are better suited to non-structural applications where their unique culm form and ornamental appearance matter more than strength. These applications may include decorative columns, indoor display elements, landscape structures, carved bamboo products, and other aesthetic applications. Likewise, species with small diameters and thin culm walls, such as Variegated bamboo and Taiwan bamboo, are more suitable for handicrafts, woven products, bamboo straws, decorative items, and other specialty products.

The results indicate that the ornamental bamboo species evaluated in this study possess physical and mechanical properties comparable to those reported for commercially utilized bamboo species. However, practical use should consider not only strength and dimensional stability but also culm dimensions and processing characteristics. As Hamid et al. (2023) emphasized, bamboo suitability for specific applications also depends on anatomical characteristics, processing behavior, durability, adhesive compatibility, and aesthetic qualities. Therefore, further studies on these properties are recommended before these ornamental bamboo species can be fully recommended for broader commercial utilization.

4. Conclusions

This study showed significant variation in the physical and mechanical properties of 12 ornamental bamboo species, indicating their potential for various applications. Mechanical properties positively correlated with relative density. Moisture content positively correlated with shrinkage and negatively correlated with relative density. The axial influence on bamboo properties varied by species. Based on strength and stiffness, Chino bamboo, Vivax bamboo, Dulcis bamboo, and Sunburn bamboo may have the greatest potential for engineered bamboo products. Black bamboo, Pink bamboo, Pole bamboo, and Buhong dilaw may have potential for furniture and semi-structural bamboo applications. Wamin bamboo, Buddha belly, Variegated bamboo, and Taiwan bamboo may be more appropriate for decorative applications. The results of the present study provide a basis for matching species to uses and support the expanded use of ornamental bamboo beyond aesthetic applications. Further studies evaluating product performance, processing characteristics, and service conditions are recommended to validate the suitability of these ornamental bamboo species for specific end uses. The proposed applications are based solely on the physical and mechanical properties evaluated in this study. Other important factors, including culm geometry, adhesive compatibility, natural durability, preservative treatability, and processing characteristics, were not evaluated and should be considered in future studies before recommending these species for specific applications.

Acknowledgments

The research was funded by the Department of Science and Technology – Forest Products Research and Development Institute (DOST–FPRDI). Bamboo planting materials were provided by the Department of Environment and Natural Resources – Ecosystems Research and Development Bureau (DENR–ERDB), the Bamboo and Rattan RDE Center of Pampanga State Agricultural University, and the Philippine Bamboo Foundation. Dr. RJ Cabangon, Mr. FC Pitargue, Mr. R. Dimapilis, Mr. J. Pigar, Mr. R. Elleva, Mr. P. Lapitan, Ms. B. Eusebio, and Ms. F. Talatala provided technical and administrative assistance in conducting this research. The funding, resources, and assistance provided by these institutions and personnel are gratefully acknowledged.

Author Contributions

O.S.M.: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition; M.A.M.M.: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition; S.A.D.: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition; D.K.M.: Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition; P.R.C.R.: Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

Not applicable.

References

Acma, L. M. C. 2017. Comparative Mechanical Properties of Selected Bamboo Species. *International Journal of Precious Engineering Research and Application* 2(1): 1–8.

Acosta, R., Montoya, J. A., and Londoño, C. A. 2021. The Influence of Thermal Treatment on the Compressive Strength and Density of Bamboo (*Guadua angustifolia* Kunth). *BioResources* 16(4): 7006–7020. DOI: 10.15376/biores.16.4.7006-7020

Adam, N., and Jusoh, I. 2019. Physical and Mechanical Properties of *Dendrocalamus asper* and *Bambusa vulgaris*. *Transactions on Science and Technology* 6(1–2): 95–101.

ASTM. 2019. *ASTM D143-52: Methods of Testing Small Clear Specimens of Timber*. ASTM International, West Conshohocken, PA, USA.

Awotwe-Mensah, M., Mitchual, S. J., Appiah-Kubi, E., Dadzie, P. K., Mensah, P., and Donkor, M. B. 2023. Assessment of the Drying Behaviour of Young and Mature *Bambusa vulgaris* from Ghana. *Advances in Bamboo Science* 5(4): 100044. DOI: 10.1016/j.bamboo.2023.100044

Bahtiar, E. T., Imanullah, A. P., Hermawan, D., Nugroho, N., and Abdurachman. 2019. Structural Grading of Three Sympodial Bamboo Culms (Hitam, Andong, and Tali) Subjected to Axial Compressive Load. *Engineering Structures* 181(6): 233–245. DOI: 10.1016/j.engstruct.2018.12.026

Bautista, B. E., Garciano, L. E. O., and Lopez, L. F. 2021. Comparative Analysis of Shear Strength Parallel to Fibers of Different Local Bamboo Species in the Philippines. *Sustainability* 13(15): 8164. DOI: 10.3390/su13158164

Bala, A., and Gupta, S. 2023. Engineered Bamboo and Bamboo-Reinforced Concrete Elements as Sustainable Building Materials: A Review. *Construction and Building Materials* 394(5): 132116. DOI: 10.1016/j.conbuildmat.2023.132116

Caicedo, C. Y., Montoya Arango, J. A., and Prieto Muriel, A. 2025. Anato-Morphological and Chemical Characterization of Bamboo (*Guadua amplexifolia* J. Presl) from San Jorge River Basin, Colombia. *Cleaner Engineering and Technology* 24(1): 100884. DOI: 10.1016/j.clet.2025.100884

Chaydarreh, K. C., Lu, Z., Li, Y., Huang, Y., Hu, C., and Zhou, Y. 2025. Bending Performance Prediction of Lightweight Composite Reinforced with Underutilized Bamboo Culm. *Journal of Building Engineering* 112: 113826. DOI: 10.1016/j.jobe.2025.113826

Cao, C., Lv, H., Yue, X., Tian, G., Cao, R., Zuo, L., Xie, F., and Xu, B. 2022. *Bamboo Pleioblastus chino var. hisauchii* Characteristics Before and After Flowering. *BioResources* 17(3): 4793–4805. DOI: 10.15376/biores.17.3.4793-4805

Chaowana, K., Wisadsatorn, S., and Chaowana, P. 2021. Bamboo as a Sustainable Building Material: Culm Characteristics and Properties. *Sustainability* 13(13): 7376. DOI: 10.3390/su13137376

DOST–PTRI. 2021. *DOST-PTRI's BambooTextilePH Brand Develops Bamboo Fibers for Textile Use*. <https://www.ptri.dost.gov.ph/9-transparency-seal/323-dost-ptri-s-bambootextilesph-brand-develops-bamboo-fibers-for-textile-use> (Apr. 01, 2026).

FMB–DENR. 2022. *Philippine Guidebook on Plant Species Suitable for Urban Greening*. Central Book Supply Inc, Manila, Philippines.

Hamid, N. H., Jawaid, M., Abdullah, U. H., and Alomari, S. 2023. Monopodial and Sympodial Bamboos Grown in Tropic and Sub-Tropic Countries: A Review. *BioResources,* 18(3): 6499–6560. DOI: 10.15376/biores.18.3.hamid

Handana, M. A. P., Surbakti, B., Harisdani, D. D., Karolina, R., and Fahreza, D. 2023. Tensile Strength of Various Bamboo Species Tested with Different Shape of Test Specimens. *Journal of Physics: Conference Series* 2421(1): 012026. DOI: 10.1088/1742-6596/2421/1/012026

Hariz, T. M. R., Santosa, I. A., Maulana, M. I., Marwanto, Prasetia, D., Hidayat, W., Lubis, M. A. R., Kim, N. H., and Febrianto, F. 2021. Effects of Resin Content on the Characteristics of Bamboo Oriented Strand Board Prepared from Strands of Betung, Ampel, and Their Mixtures. *Jurnal Sylva Lestari* 9(3): 454–465. DOI: 10.23960/jsl.v9i3.520

Huang, X., Li, F., De Hoop, C. F., Jiang, Y., Xie, J., and Qi, J. 2018. Analysis of *Bambusa rigida* Bamboo Culms Between Internodes and Nodes: Anatomical Characteristics and Physical–Mechanical Properties. *Forest Products Journal* 68(2): 157–162. DOI: 10.13073/fpj-d-17-00035

ISO. 2019. *Bamboo structures - Determination of Physical and Mechanical Properties of Bamboo Culms - Test Methods (22157:2019)*. International Organization for Standardization, Geneva.

Iswanto, A. H., Nabila, N., Elfina, R., Hakim, L., Sucipto, T., Aristri, M. A., Lubis, M. A. R., Fatriasari, W., Sutiawan, J., Darwis, A., Rogoziński, T., Hua, L. S., Chen, L. W., and Antov, P. 2025. Characteristics of Three Bamboo Species and Their Potential as Raw Materials for Oriented Strand Board Production. *Journal of Renewable Materials* 13(11): 2253–2279. DOI: 10.32604/jrm.2025.02025-0058

Irader, M. K. P. 2015. *Raising Ornamental Bamboo for Livelihood*. DOST–PCAARRD. <https://pcaarrd.dost.gov.ph/index.php/quick-information-dispatch-qid-articles/raising-ornamental-bamboo-for-livelihood> (Apr. 01, 2026).

Javadian, A., Smith, I. F. C., Saeidi, N., and Hebel, D. E. 2019. Mechanical Properties of Bamboo Through Measurement of Culm Physical Properties for Composite Fabrication of Structural Concrete Reinforcement. *Frontiers in Materials* 6: 15. DOI: 10.3389/fmats.2019.00015

Jimenez, J. P., Macalinao, M. G. M., and Sapin, G. N. 2021. Physico-Mechanical Properties of Two Philippine Bamboo Thermally Modified in a Steam Environment. *Philippine Journal of Science* 150(1): 171–182. DOI: 10.56899/150.01.14

Liu, P. C., Zhou, Q. S., Tian, J. F., Li, W., and Fu, F. Y. 2021. Experimental Study on Bending Resistance of Original Bamboo Material. *Journal of Architecture and Civil Engineering* 38(4): 101–109. DOI: 10.19815/j.jace.2021.03041

Natividad, R. A., and Jimenez, J. P. 2015. Development of Laminated Buho [*Schizostachyum lumampao* (Blanco) Merr.] Lumber. *Philippine Forest Products Journal* 6(1): 78–89.

Nugroho, N., Kartini, and Bahtiar, E. T. 2021. Cross-Species Bamboo Grading Based on Flexural Properties. IOP Conference Series: Earth and Environmental Science 891(1): 012008. DOI: 10.1088/1755-1315/891/1/012008

Opeña, J. M., Bumanglag, R. A., and Cabang, V. M. T. 2023. Morphological, Phytochemical, and Molecular Profiling of Bamboo Species Growing in Various Ecosystems of Cagayan Province, Luzon, Philippines. *Biodiversitas* 24(8): 4342–4358. DOI: 10.13057/biodiv/d240816

Putri, A. R., Alam, N., Adzkia, U., Amin, Y., Darmawan, I. W., and Karlinasari, L. 2023. Physical and Mechanical Properties of Oriented Flattened Bamboo Boards from Ater (*Gigantochloa atter*) and Betung (*Dendrocalamus asper*) Bamboos. *Jurnal Sylva Lestari* 11(1): 1–21. DOI: 10.23960/jsl.v11i1.614

R Core Team. 2022. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna.

Roxas, C. A. 2012. *Handbook on Erect Bamboo Species Found in the Philippines*. DENR–ERDB, Los Baños, Philippines.

Roxas, C. A., Tangan, F. T., and Virtucio, F. D. 2000. *DENR Recommends: Ornamental Bamboos for Urban Parks*. Vol. 9. DENR–ERDB, Los Baños, Philippines.

Salzer, C., Wallbaum, H., Alipon, M., and Lopez, L. F. 2018. Determining Material Suitability for Low-Rise Housing in the Philippines: Physical and Mechanical Properties of *Bambusa blumeana*. *BioResources* 13(1): 346–369. DOI: 10.15376/biores.13.1.346-369

Santos, G. 2018. *Bamboo Propagation and Plantation Establishment*. 5-Day National Trainers' Training on Bamboo Propagation, Plantation Development, and Clump Management, Los Baños, Philippines.

Siam, N. A., Uyup, M. K., Husain, H., Mohmod, A. L., and Awalludin, M. F. 2019. Anatomical, Physical, and Mechanical Properties of Thirteen Malaysian Bamboo Species. *BioResources* 14(2): 3925–3943. DOI: 10.15376/biores.14.2.3925-3943

Sulaiman, M. S., Mhd. Ramle, S. F., Hashim, R., Sulaiman, O., Mohamad Amini, M. H., and Boon, J. G. 2018. The Classical Mechanics Engineered of *Bambusa vulgaris* and *Schizostachyum brachycladum*. *Journal of Tropical Resources and Sustainable Science* 6(2): 57–61. DOI: 10.47253/jtrss.v6i2.561

Tang, T. K. H., Trinh, H. M., and Nguyen, T. T. H. 2022. Mould Resistance of the Bamboo *Thyrsostachys siamensis* Treated with Oleoresin Heat. *Journal of Forestry Science and Technology* 13: 103–108. DOI: 10.55250/jo.vnuf.2022.13.103-108

Villareal, J. F., Marasigan, O. S., Mendoza, R. C., Alipon, M. A., and Abasolo, W. P. 2020. Morphological, Anatomical, and Physical Properties of Iron Bamboo (*Guadua angustifolia*) Grown in the Philippines. *Philippine Journal of Science* 149(3A): 1005–1013. DOI: 10.56899/149.3a.25

Xu, W., and Wang, S. 2023. Research Progress of *Phyllostachys vivax* cv. Aureocaulis. *Theoretical and Natural Science* 7(1): 116–19. DOI: 10.54254/2753-8818/7/20230122

Yuan, J., Chen, L., Mi, B., Lei, Y., Yan, L., and Fei, B. 2023. Synergistic Effects of Bamboo Cells During Shrinkage Process. *Industrial Crops and Products* 193: 116232. DOI: 10.1016/j.indcrop.2022.116232

Zakikhani, P., Zahari, R., Sultan, M. T. B. H., and Majid, D. L. A. 2017. Morphological, Mechanical, and Physical Properties of Four Bamboo Species. *BioResources* 12(2): 2479–2495. DOI: 10.15376/biores.12.2.2479-2495

Zhu, J., and Yang, L. 2025. Progress in the Study of Dry Shrinkage Deformation and Drying Stress of Raw Bamboo. *BioResources* 20(1): 2304–2320. DOI: 10.15376/biores.20.1.zhu