



Effect of thermal modification using steam on the physico-mechanical properties of *Gigantochloa levis* and *Bambusa vulgaris*

Juanito P. Jimenez, Jr.,^{1*} , Michaela Germaine M. Macalinao¹ 

ABSTRACT: Bamboo is a sustainable construction material, but is limited by its hygroscopicity and susceptibility to biodegradation. This study evaluated the effects of steam thermal modification (TM) at 175 °C and 200 °C for 30 min on the physico-mechanical properties of *Gigantochloa levis* and *Bambusa vulgaris*. Node and internode sections were tested for physical (moisture content, thickness swelling, water absorption, relative density) and mechanical (flexural, compression, tensile) properties using a completely randomized factorial design. TM significantly improved dimensional stability by reducing moisture content, water absorption, and radial swelling. Relative density was mainly influenced by species. While flexural modulus of elasticity remained unaffected, the modulus of rupture decreased at 200 °C. Nodal sections consistently exhibited lower tensile strength than internodes, with the lowest values occurring at 200 °C. Conversely, compression strength significantly increased after TM. Overall, moderate thermal modification (175 °C for 30 min) provided the optimal balance between enhanced dimensional stability and mechanical performance for both species.

Keywords: Bamboo Modification, Dimensional Stability, Flexural, Tensile, Compression

Buhar kullanılarak yapılan termal modifikasyonun *Gigantochloa levis* ve *Bambusa vulgaris*'in fiziko-mekanik özelliklerine etkisi

ÖZ: Bambu, sürdürülebilir bir yapı malzemesidir ancak higroskopikliği ve biyolojik bozunmaya yatkınlığı nedeniyle sınırlamalara sahiptir. Bu çalışma, *Gigantochloa levis* ve *Bambusa vulgaris*'in fiziko-mekanik özelliklerine 175 °C ve 200 °C'de 30 dakika süreyle buharla termal modifikasyonun (TM) etkilerini değerlendirmiştir. Düğüm ve düğüm arası bölümler, tamamen rastgele faktöriyel tasarım kullanılarak fiziksel (nem içeriği, kalınlığına şişmesi, su emme, bağıl yoğunluk) ve mekanik (eğilme, basınç, çekme) özellikler açısından test edilmiştir. TM, nem içeriğini, su emmeyi ve radyal şişmeyi azaltarak boyutsal kararlılığı önemli ölçüde iyileştirmiştir. Bağıl yoğunluk esas olarak türden etkilendi. Eğilmede elastikiyet modülü etkilenmeden kalırken, eğilme direnci 200 °C'de azaldı. Düğüm bölümleri, düğüm arası bölümlere göre sürekli olarak daha düşük çekme dayanımı göstermiş ve en düşük değerler 200 °C'de görülmüştür. Buna karşılık, basınç direnci TM'den sonra önemli ölçüde artmıştır. Genel olarak, orta düzeyde termal modifikasyon (30 dakika 175 °C), her iki tür için de gelişmiş boyutsal kararlılık ve mekanik performans arasında en uygun dengeyi sağlamıştır.

Anahtar kelimeler: Bambu Modifikasyonu, Boyutsal Stabilite, Eğilme, Çekme, Basınç

1 Introduction

Bamboo is among the most abundant renewable resources in the Philippines. Due to its rapid growth, renewability, workability, and favorable physico-mechanical properties, it is widely utilized in handicrafts, furniture, structural components, engineered composites, and flooring applications (Alipon et al., 2011; Razal et al., 2012; Awalluddin et al., 2017; Jais et al., 2023, Halip et al., 2025). Recognized as a sustainable alternative construction material, bamboo exhibits a strength-to-weight ratio comparable to wood and steel (Ogunbiyi et al., 2015; Jimenez et al., 2021). However, similar to wood, untreated bamboo is a lignocellulosic and hygroscopic material. It readily absorbs and releases moisture in response to fluctuating environmental conditions, resulting in poor dimensional stability (Liese and Tang, 2015; Jimenez and Ramos 2024). In addition, its carbohydrate-rich fiber composition makes it highly susceptible to insect attack and fungal decay.

Numerous modification techniques have been explored to enhance the biological durability, weather resistance, and physico-mechanical properties of bamboo. These include traditional smoking (Ramful and Sakuma 2021), thermal treatments using steam, oil, or air (Bui et al., 2017; Jimenez et al., 2021; Yang et al., 2022; Lou et al., 2023; Jimenez and Ramos 2024), and chemical treatments such as plasma surface modifications (Rao et al., 2018), resin impregnation (Li et al., 2020), and nanomaterial-based treatments (Ba et al., 2023). A recent study conducted by Mangurai et al. (2022) also explored the effect of post-thermal treatment to enhance physico-mechanical properties of bamboo oriented strand board (OSB) and reported significant improvements on the dimensional stability of the material. Pangestu et al. (2026) conducted combined treatments involving boric acid equivalent impregnation, heat treatment (60 °C, 150 °C, and 180 °C), and vegetable oils (linseed and neem oil) to improve the resistance of bamboo against biological attacks. Despite these advancements, many technologies remain limited in industrial-scale application.

Thermal modification (TM) has gained considerable attention as an eco-friendly and cost-effective single-stage process that improves bamboo's dimensional stability while retaining acceptable mechanical integrity. The TM process typically involves heating the material at temperatures ranging from 160 °C to 240 °C in an oxygen-depleted environment without requiring external hazardous chemicals (Tang et al., 2019; Zheng et al., 2023). Initially commercialized in Europe for wood treatment, TM has evolved into several patented industrial systems, including ThermoWood, PlatoWood, Retified Wood, Oil Heat Treatment (OHT), Feuchte-Wärme-Druck (FWD), Perdure, and VacWood (Hill, 2006; Sandberg et al., 2017). In the Philippines, beyond traditional smoking practices localized within rural communities, the application of steam- and oil-based thermal processing is being actively researched to facilitate wider commercial adoption.

Despite the growing body of literature on bamboo thermal modification, existing studies have focused on a limited selection of commercially viable species. Comparatively fewer studies have examined *Gigantochloa levis* (Blanco) Merr. and *Bambusa vulgaris* Schrad. ex J.C. Wendl., particularly with respect to their raw physical and mechanical performance. Given the commercial importance of both species in the Philippines, a clear knowledge gap exists regarding how culm characteristics—specifically between nodal and internodal regions—influence their physical and mechanical responses to heat. Addressing these gaps are critical for improving the understanding of species-specific and morphological variations that govern treatment performance and end-use applications of bamboo culms and slats.

This research aimed to determine the effects of TM in a saturated-steam environment on the physico-mechanical properties of *G. levis* and *B. vulgaris*. The treatments were carried out at 175 °C and 200 °C for a fixed duration of 30 min, while concurrently evaluating the structural influences of nodal versus internodal regions. The physical properties evaluated included moisture content (MC), relative density (RD), water absorption (WA), and radial thickness swelling (TSw). The mechanical properties assessed were compression strength (CS) parallel to the grain, flexural characteristics—specifically modulus of elasticity (MOE) and modulus of rupture (MOR)—and longitudinal tensile strength (TS). Ultimately, this research intends to provide foundational data for optimizing bamboo modification techniques to expand their viability in industrial applications.

2 Materials and Methods

2.1 Sample collection and preparation

Mature bamboo poles (3-4 years old) of species *G. levis* and *B. vulgaris* were locally sourced in areas of Laguna, and Rizal in the Philippines. The bottom, middle, and top portions of the culms were collected and brought to Forest Products Research and Development Institute (FPRDI) for conditioning and processing. Samples were air-dried to equilibrium moisture content (EMC) for two months before TM. MC was then determined using the FPRDI-developed wood moisture meter (FPRDI FA 507), with a reported measurement accuracy of $\pm 1\%$.

2.2 Thermal modification process

The bottom portions of the bamboo culms were used for this study, as this section represents the primary material used for commercial structural applications for engineered laminated bamboo due to its superior wall thickness. Furthermore, restricting sampling to the basal region minimizes height-dependent physico-mechanical property variations within the species. Poles (116 cm length) were cut with an industrial-grade pole cutter to fit in the cylindrical TM chamber. The TM treatment settings used were 175 °C–30 min and 200 °C–30 min. Eight poles per batch were loaded and TM process was carried out by introducing steam generated from a mini boiler into the closed chamber. Three 4 kW heaters at the base of the cylinder were then activated to raise the system to the target temperature gradually. Internal pressure was automatically released upon reaching 30 psi (2.11 kg/cm²). The process was monitored for 3 h, including 2 h to raise the temperature from ambient to the target level and 1 h for cooling the chamber down to 50 °C. The poles were then unloaded and processed as depicted in Fig. 1. The process flow is discussed further in the following subsections.

2.3 Physical property tests

Defect-free TM poles were conditioned along with the control samples for 1 mo in a room with temperature of 23 ± 2 °C and relative humidity (RH) of $65 \pm 5\%$. Samples for testing were prepared in accordance with ASTM Standard Test Methods for Small Clear Specimens of Timber (D143-14) with modifications in specimens' dimensions. Physical tests were MC, RD, WA, and TSw.

2.3.1 Moisture content and relative density

Ten (10) replicates from the node and internode portions were used to determine the MC and RD. Specimens were cut to actual dimensions of culm wall thickness (CWT) x 25 mm (width) x 25 mm (length). The initial mass (W_i) was measured using a digital top loading balance while volume (V_m) was determined by water displacement. After volume

determination, the samples were oven-dried at 103 ± 2 °C until a constant oven-dry weight (W_o). MC was calculated as the mass loss expressed as a percentage of W_o , whereas relative density (RD) was computed as the ratio of W_o to V_m , divided by the density of water.

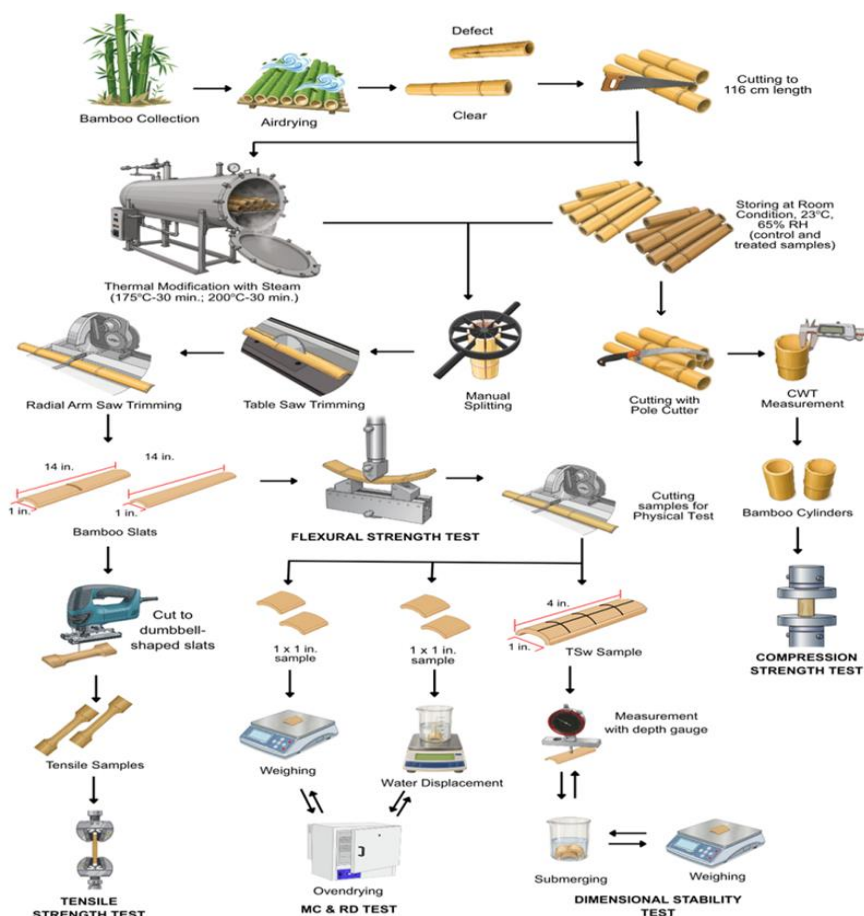


Figure 1. Schematic diagram of the study's experimental procedure

2.3.2 Hygroscopicity and dimensional stability

Hygroscopicity, expressed as WA, and dimensional stability, as radial TSw, were determined following ASTM D 143 (2014) with minor modifications. Specimens ($CWT \times 2.54 \text{ cm} \times 10.16 \text{ cm}$) were prepared with 10 replicates per treatment. All samples were oven-dried at 103 ± 2 °C to constant mass. Oven-dry mass and radial TSw were measured using a digital balance and Mitutoyo Digimatic indicator. Samples were submerged horizontally in distilled water with a weight restraint. After 24 h, they were removed, drained for 10 min, and surface water was wiped off. WA and TSw were calculated from the differences in mass and thickness before and after submersion, expressed as percentages of the initial weight (W_i) and thickness.

2.4 Mechanical property tests

2.4.1 Compression strength

Ten (10) node and internode samples were prepared per species for control and thermally modified groups. CWT was measured using a digital caliper and served as the basis of the specimen length, which was calculated as ten times the CWT. Testing was performed using a 300 kN Shimadzu Universal Testing Machine.

2.4.2 Flexural strength

Flexural testing was performed in accordance with ASTM D143-14, using modified specimen dimensions suited to the bamboo configuration. Bamboo slats (35.56 cm length) were prepared from the control and TM batches. For each species, 10 slats with nodes and 10 from the internode region were tested, resulting in a total of 120 samples for flexural strength evaluation. Prior to testing, specimen dimensions were measured using a digital caliper. Flexural properties, specifically the MOE and MOR, were determined using a Shimadzu universal testing machine (UTM) under center-point loading, with a span length of 30.48 cm and a loading speed of 15 mm/min. MOE and MOR were calculated using Equations 1 and 2, respectively.

$$MOE = \frac{PL^3}{4bd^3\Delta} \quad (1)$$

$$MOR = \frac{3WL}{2bd^2} \quad (2)$$

where MOE is Modulus of Elasticity (GPa), MOR is Modulus of Rupture (MPa), P is load at proportional unit (N), W is the maximum load (N), L is the span (mm), b is the width (mm), d is the depth (mm), and Δ is the deflection at proportional limit (mm).

2.4.3 Tensile strength

Tensile test specimens were prepared in a modified dumbbell configuration based on ASTM D143-14. Five (5) each of the internode and node samples from the control and thermally modified culms were machined into dumbbell-shaped slats with an overall length of 254 mm (10 in) and a reduced-section width of 9.5 mm (3/8 in). Width of 25.4 mm (1 in) was retained at both ends to facilitate gripping during testing, while the thickness corresponded to the actual CWT of each bamboo sample. The test speed of the Shimadzu UTM was set at 1.3 mm/min for tensile tests.

2.4.4 Data analysis

The statistical analysis and box plots were generated using Origin Pro 2026. Two-factor factorial design in a completely randomized set-up was applied to WA and TSw, while three-factor factorial design was used for MC, RD, CS, MOE, MOR and TS. The factors were species (*G. levis*, *B. vulgaris*), culm region (node, internode) characteristics, and treatment (control, 175 °C – 30 min., 200 °C – 30 min.). Before analysis, the assumptions of ANOVA were verified; normality of the data distribution was assessed using the Shapiro-Wilk test, while homogeneity of variances was evaluated using Levene's test. The data were subsequently analyzed using Analysis of Variance (ANOVA), followed by Tukey's Honest Significant Difference (HSD) test at a 95% confidence level.

3 Results and Discussion

3.1 Physical properties

3.1.1 MC and RD

Three-way ANOVA (Table 1) revealed that species, culm region, and treatment significantly affected the MC. However, the interactions of the three factors were insignificant. Node samples exhibited significantly higher MC than internode samples (Fig. 2), which may be attributed to their wider cell lumens that can retain more moisture (Huang et al. 2017).

Table 1. Three-way ANOVA on the MC and RD of *G. levis* and *B. vulgaris*.

Sources of Variation	df	MC (%)		RD	
		F- value	p-value	F-value	p-value
Species (S)	1	14.145	0.0003*	36.409	<0.0001*
Culm region (C)	1	70.456	<0.0001*	0.569	0.452 ns
Treatment (T)	2	386.225	<0.0001*	5.448	0.0056 *
S x C	1	0.675	0.413 ns	0.832	0.363 ns
S x T	2	7.835	0.0006*	8.061	0.0005 *
C x T	2	0.221	0.802 ns	2.672	0.0737 *
S x C x T	2	1.588	0.209 ns	0.216	0.806 ns

* - significant, ns - not significant

MC decreased with increasing treatment severity, from 9.21%–11.23% in the control to 5.18%–7.78% after treatment at 175 °C for 30 min and further to 3.21%–5.64% after treatment at 200 °C for 30 min, indicating reduced moisture affinity following TM. Similar trends were reported by Jimenez et al. (2021), Ramos et al. (2022), Jimenez and Ramos (2024), and Jimenez and Rizare (2024). The reduction in MC suggests that TM reduced the hydroxyl groups or active sites available for bound-water adsorption due to chemical changes induced during TM (Jimenez and Razal 2004, Wu et al. 2021, Xiao et al. 2022). Such reductions are advantageous for engineered and laminated bamboo products, as lower moisture uptake can contribute to dimensional stability under fluctuating humidity conditions.

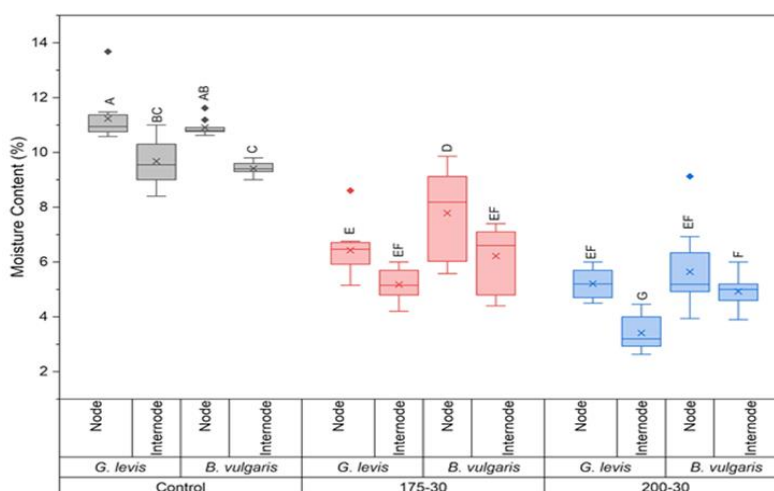


Figure 2. Moisture content (MC) of *G. levis* and *B. vulgaris* in node and internode sections under different TM settings. Same letters indicate no significant difference at $\alpha = 0.05$.

RD was significantly affected by species and treatment, whereas the culm region and most interacting factors showed no significant effects. However, a significant interaction between species and treatment indicated that the response to thermal modification differed between *B. vulgaris* and *G. levis*. Across all evaluated settings, *B. vulgaris* consistently exhibited higher RD values than *G. levis* (Fig. 3). The highest RD was recorded in *B. vulgaris* node samples treated at 200 °C for 30 min (0.751), whereas the lowest occurred in *G. levis* internode samples subjected to the same treatment (0.497). Although node specimens displayed a trend toward slightly higher RD values than internode samples within identical treatment groups, these variations were not statistically significant.

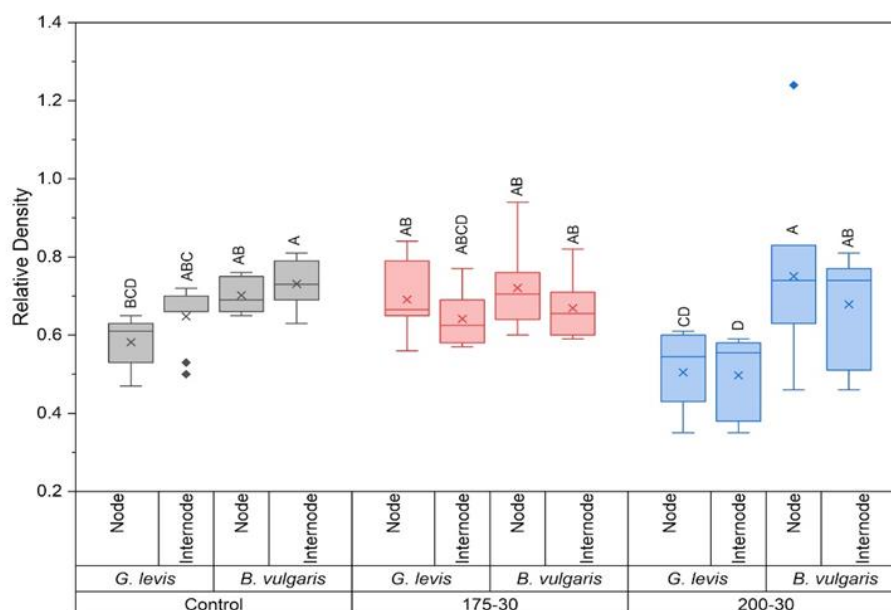


Figure 3. Relative density of *G. levis* and *B. vulgaris* in node and internode sections under different TM settings. Same letters indicate no significant difference at $\alpha = 0.05$.

In *G. levis*, RD generally decreased with increasing treatment severity, particularly at 200°C–30 min. This trend was also documented by Jimenez and Ramos (2024) for Giant Bamboo (*Dendrocalamus asper*). This reduction at higher temperatures may be associated with the thermal degradation of hemicelluloses, which possess lower thermal stability due to their branched and amorphous structure, making them more susceptible to decomposition (Iswanto et al. 2022; Wu et al. 2021, Xiao et al. 2022). The wider distribution observed in the thermally modified samples suggests that heat treatment affected the material non-uniformly, possibly due to inherent anatomical and chemical variability within the bamboo culm.

3.1.2 Water absorption and thickness swelling

Two-way ANOVA revealed that the WA of *G. levis* and *B. vulgaris* did not differ significantly, whereas the thermal modification significantly reduced WA values regardless of the species (Table 2). The non-significant interaction between species and treatment further indicates that both bamboo species responded similarly to treatment conditions. Untreated samples exhibited the highest WA values (Fig. 4a), with means of 28.34% for *G. levis* and 25.57% for *B. vulgaris*. In contrast, TM samples showed lower WA values ranging from 17.83 to 22.00%, corresponding to an approximate reduction of 22%–36% relative to the control samples. This reduction suggests decreased hygroscopicity following TM.

Table 2. Two-Way ANOVA results for WA and TSw of *G. levis* and *B. vulgaris*.

Sources of Variation	df	WA (%)		TSw (%)	
		F- value	p-value	F-value	p-value
Species (S)	1	1.836	0.181ns	7.457	0.0085*
Treatment (T)	2	10.134	0.00018*	11.600	<0.0001*
S x T	2	0.327	0.7224 ns	2.305	0.1100 ns

* - significant, ns - not significant

For TSw, ANOVA in Table 2 showed that species and treatment affected TSw, while interactions were not. Untreated samples exhibited the highest swelling, while TSw progressively decreased with increasing treatment temperature in both species. The greatest reduction was observed at 200 °C for 30 min, where mean TSw decreased from 12.82% to 2.46% in *G. levis* and from 6.98% to 2.20% in *B. vulgaris*, indicating substantial improvements in dimensional stability (Fig. 4b).

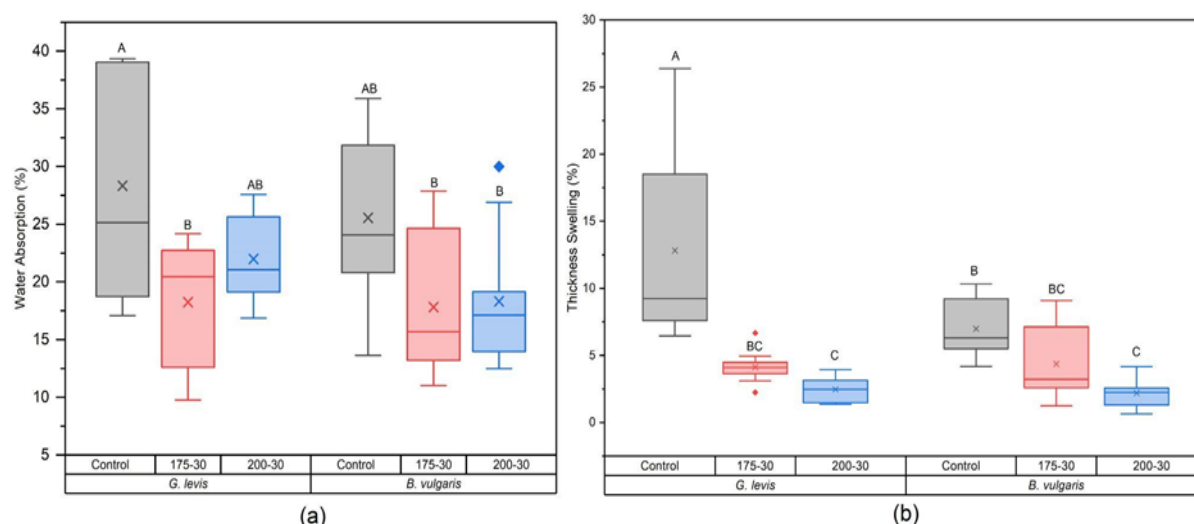


Figure 4. Box-and-whisker plot of (a) Water Absorption and (b) Radial Thickness Swelling of *G. levis* and *B. vulgaris* under different TM settings. Same letters indicate no significant difference at $\alpha = 0.05$.

Results in WA and TSw indicate that TM significantly altered the chemical components of the bamboo cell wall matrix. At elevated processing temperatures, highly hydrophilic hemicelluloses undergo thermal degradation and hydrolysis, drastically reducing the availability of free hydroxyl (–OH) groups in the hemicellulose and amorphous regions of the cellulose network (Hill, 2006; Cermak et al., 2015; Wu et al., 2021; Xiao et al., 2022). This degradation decreases the material's accessible water-binding sites, directly suppressing hygroscopicity (FTA, 2003; Jimenez and Ramos, 2024). Concurrently, the relative proportion of crystalline cellulose and lignin increases due to the mass loss of volatile hemicellulose fractions (Jimenez and Razal, 2004; Wu et al., 2021; Xiao et al., 2022). The resulting cross-linking reactions within the lignin network create a more rigid, hydrophobic matrix, thereby limiting moisture absorption and enhancing dimensional stability (Wu et al., 2021; Yu et al., 2023). These structural transformations strongly align with previous TM mechanisms reported by Jimenez et al. (2021), Ramos and Jimenez (2025) and Zheng et al. (2025).

3.2 Mechanical properties

3.2.1 Compression strength

Results of the CS test on the untreated and thermally modified *G. levis* and *B. vulgaris* are shown in Fig. 5. According to the ANOVA results in Table 3, CS was significantly affected by the TM treatment, while species and culm region were insignificant.

The mean compression values showed that both thermally modified samples outperformed the untreated control (Fig. 5a). Samples treated at 175 °C for 30 min exhibited the highest compression strength (55.73 MPa), followed by those treated at 200 °C for 30 min (53.45 MPa). Although the two treatments did not differ significantly, both yielded significantly

higher values than the control (43.78 MPa). Previous studies (Zhang et al. 2013; Tang et al. 2019; Zheng et al. 2025) have reported that compressive strength improves at treatment temperatures ranging from 175 to 180 °C due to the volumetric shrinkage of the material, which reduces porosity and promotes more efficient stress distribution. At higher treatment severities, however, degradation of structural components may offset these benefits and limit the strength improvements.

Table 3. Three-Way ANOVA results for the compression strength of *G. levis* and *B. vulgaris*.

Sources of Variation	df	Compression Strength (MPa)	
		F- value	p-value
Species (S)	1	1.252	0.266 ns
Culm region (C)	1	0.514	0.475 ns
Treatment (T)	2	6.950	0.0015 *
S x C	1	1.549	0.216 ns
S x T	2	3.531	0.0327 *
C x T	2	0.369	0.693 ns
S x C x T	2	0.136	0.872 ns

* - significant, ns - not significant

Tukey's HSD test indicated no significant three-way interaction among species, culm region, and treatment (Fig. 5b). Nevertheless, higher compression values observed in *B. vulgaris* internode treated at 200-30 (61.35 MPa) and *G. levis* internode at 175-30 (60.32 MPa) suggest that these treatment conditions provided an optimal balance between cell wall stiffening and thermal degradation. Excessive heat exposure can initiate degradation of structural carbohydrates, which may explain why 200-30 did not significantly exceed 175-30 treatment.

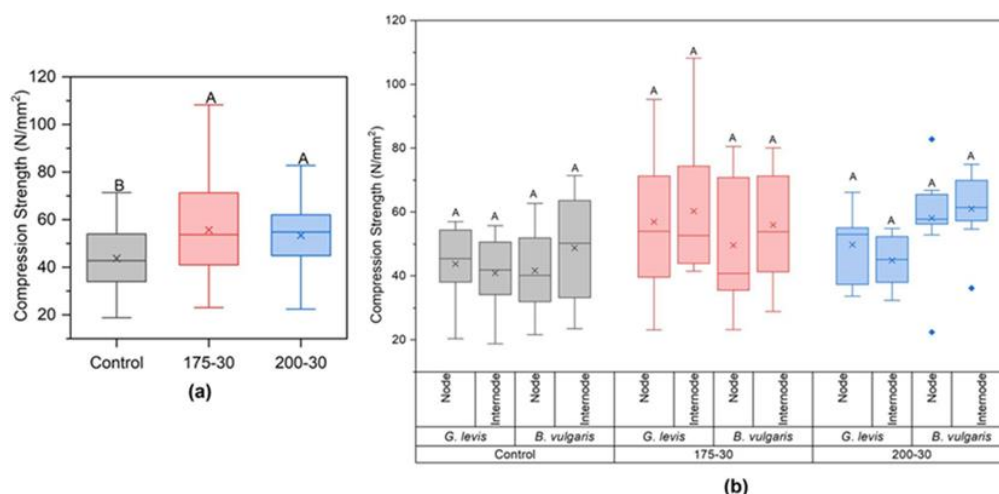


Figure 5. Box and whiskers plot of the compression strength grouped according to (a) treatment: control, 175-30 and 200-30 and (b) interactions of the three factors: species, culm region, and treatment. Same letters indicate no significant difference at $\alpha = 0.05$.

3.2.2 Flexural Strength - MOE and MOR

The flexural MOE of untreated and thermally modified bamboo ranged from 5.03 to 7.70 GPa (Fig. 6). Three-way ANOVA showed that species, culm region, TM treatment, and their interactions did not significantly affect MOE (Table 4). Consistent with this finding, Tukey's HSD test grouped all treatment combinations within the same statistical category.

The highest mean MOE was recorded in *B. vulgaris* node samples treated at 175 °C for 30 min (7.70 GPa), followed by untreated *B. vulgaris* internode samples (7.12 GPa). Meanwhile, the lowest MOE was observed in *G. levis* node samples treated at 200 °C for 30 min (5.03 GPa). Despite these numerical differences, the results suggest that TM at 175 °C and 200 °C for 30 min did not adversely affect the stiffness or elastic behavior of either bamboo species.

Table 4. Three-Way ANOVA results for the MOE & MOR of *G. levis* and *B. vulgaris*

Sources of Variation	df	MOE (GPa)		MOR (MPa)	
		F- value	p-value	F-value	p-value
Species (S)	1	1.241	0.268 ns	1.978	0.162 ns
Culm region (C)	1	2.281	0.134 ns	4.836	0.030 *
Treatment (T)	2	1.709	0.186 ns	19.433	<0.0001*
S x C	1	1.405	0.239 ns	0.227	0.635 ns
S x T	2	0.467	0.628 ns	1.087	0.341 ns
C x T	2	2.378	0.098 ns	4.601	0.012 *
S x C x T	2	0.467	0.629 ns	0.392	0.676 ns

* - significant, ns - not significant

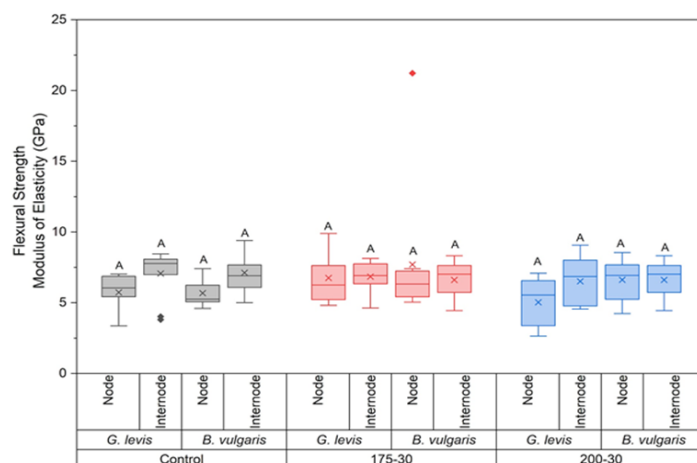


Figure 6. Flexural MOE of *G. levis* and *B. vulgaris* in node and internode sections under different TM settings. Same letters indicate no significant difference at $\alpha = 0.05$.

Similar findings were reported by Liang et al. (2024), who observed minimal changes in MOE with increasing treatment intensity. This response has been attributed to the balance between hemicellulose degradation and the relative increase in lignin content during TM process (Zhang et al. 2012; Zhang et al. 2013; Liang et al. 2024). Although hemicellulose degradation may reduce cell-wall reinforcement, the increase in relative lignin content can compensate for this loss, resulting in little to no net change in stiffness.

In contrast, MOR was significantly affected by node presence and TM, while species and three-way interactions showed no significant effect (Table 4). The highest MOR was recorded in *G. levis* internode samples (84.61 MPa) and *B. vulgaris* node samples (83.97 MPa) treated at 175 °C for 30 min (Fig. 7). Conversely, *G. levis* node samples treated at 200 °C for 30 min exhibited the lowest MOR (34.74 MPa) and formed a distinct statistical group, showing a substantial reduction in flexural strength at higher treatment severity. These results suggest that treatment at 175 °C for 30 min maintained or slightly improved bending strength, whereas treatment at 200 °C for 30 min led to noticeable reductions in MOR.

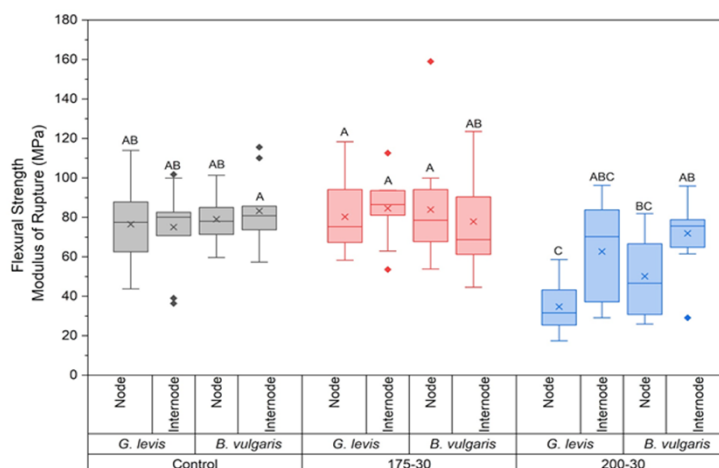


Figure 7. Flexural strength (MOR) of *G. levis* and *B. vulgaris* in node and internode sections under different TM settings. Same letters indicate no significant difference at $\alpha = 0.05$.

Internode sections exhibited higher MOR values than node sections, owing to their more uniform fiber arrangement and vascular bundle distribution; conversely, the structural discontinuities present in nodes act as stress concentration areas during bending. While MOE remained relatively unaffected by TM, MOR proved highly sensitive to increasing treatment severity, particularly at 200 °C for 30 min.

Consequently, industrial users must restrict structural processing to the moderate 175 °C regime to maintain a safe load-bearing capacity, as severe treatment at 200 °C dramatically narrows the safety margin against sudden, catastrophic bending failures. Alternatively, the 200 °C treatment should be strategically reserved for non-load-bearing, high-moisture applications where maximizing dimensional stability outweighs strength loss.

3.2.3 Tensile Strength

TS was significantly influenced by species, culm region, and treatment severity. However, their interactions were not statistically significant, indicating a similar response pattern of *G. levis* and *B. vulgaris* on TM (Table 5). Under control conditions, both species exhibited high TS values, particularly within the internode sections (Fig. 8). The highest TS was recorded in the internodes of *B. vulgaris* (123.80 MPa), followed by *G. levis* (112.76 MPa). Across all evaluated conditions, internodes consistently exhibited superior TS compared to nodal regions. This disparity was far more pronounced in tensile testing than in compression and flexural configurations, highlighting the extreme sensitivity of TS to nodal fiber deviations and underscoring the critical importance of component selection in engineered applications.

Table 5. Three-Way ANOVA results for the tensile strength of *G. levis* and *B. vulgaris*

Sources of Variation	df	Tensile Strength (MPa)	
		F- value	p-value
Species (S)	1	26.639	<0.0001*
Culm region (C)	1	24.859	<0.0001*
Treatment (T)	2	33.852	<0.0001*
S x C	1	2.361	0.131 ns
S x T	2	2.289	0.112 ns
C x T	2	0.901	0.413 ns
S x C x T	2	1.315	0.278 ns

* - significant, ns - not significant

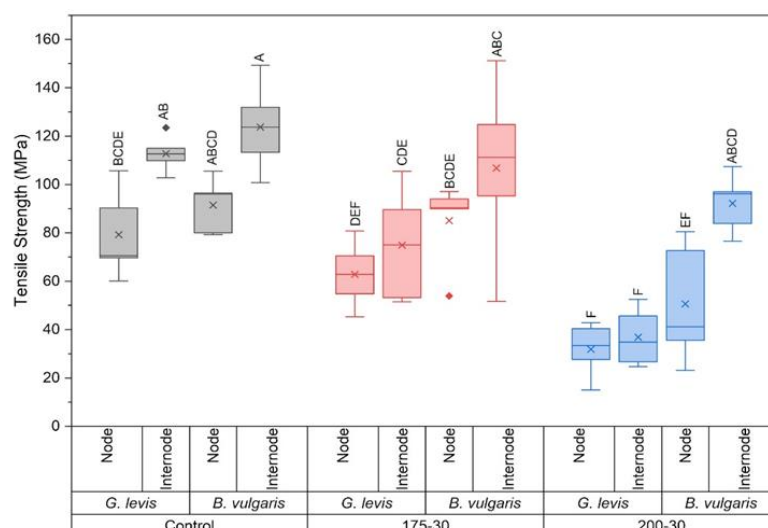


Figure 8. Tensile strength of *G. levis* and *B. vulgaris* in node and internode sections under different TM settings. Same letters indicate no significant difference at $\alpha = 0.05$.

TM at 175 °C for 30 min generally reduced the TS of *G. levis*, resulting in decreases of 33.53% for nodes and 20.71% for internodes. In contrast, *B. vulgaris* demonstrated superior TS retention, with minor reductions in the internode (13.7%) and node (7%) regions that remained statistically comparable to the untreated control. Specifically, *B. vulgaris* internode specimens treated at 175 °C for 30 min maintained high tensile resilience but exhibited wide data scatter. While this variability suggests that moderate thermal treatment did not uniformly compromise the structural fibers, the small sample size ($n = 5$ per group) represents a limitation in capturing the full population variance, meaning these localized retention trends should be interpreted with caution.

At 200 °C for 30 min, however, TS declined drastically in both species, with *G. levis* suffering the most severe degradation. In *B. vulgaris*, TS decreased to 92.22 MPa (internode) and 50.63 MPa (node), representing reductions of 25.51% and 44.65%, respectively. Significantly greater losses were observed in *G. levis*, where values plummeted to 36.88 MPa (internode) and 31.86 MPa (node)—equivalent to 67.29% and 59.81% reductions. The lowest TS occurred in the heat-treated *G. levis* node, confirming that severe high-temperature exposure combined with nodal microstructural discontinuities severely compromises longitudinal tensile resistance. Although the magnitude of these extreme percentage drops strongly points to severe thermal degradation of the hemicelluloses (Wu et al., 2021; Xiao et al., 2022) and vascular fiber network, the limited number of replicates dictates that these precise values be treated as indicative of major structural weakening rather than definitive absolute thresholds.

Consequently, for industrial applications demanding high tensile performance, such as parallel-strand bamboo composites or structural truss elements, raw material processing must be carefully segmented by species, prioritizing *B. vulgaris* over *G. levis* due to its vastly superior fiber resilience at moderate temperatures. Furthermore, manufacturing lines must strategically isolate or relegate node-containing segments away from high-tensile zones, as severe heat combined with nodal fiber deviations creates critical, failure-prone weak points in engineered structural products.

4. Conclusion

Based on the findings of this study, the following can be drawn regarding the effects of steam TM on the physico-mechanical properties of *G. levis* and *B. vulgaris*:

- **Physical Properties:** TM significantly improved the dimensional stability of both species by reducing MC, WA, and TSw. RD was governed primarily by species characteristics rather than treatment intensity, with *B. vulgaris* consistently maintaining higher density values than *G. levis*.
- **Elastic Stiffness:** The flexural MOE was not significantly altered by TM, demonstrating that the baseline elastic stiffness of both bamboo species is structurally resilient to heat treatments up to 200 °C.
- **Strength Degradation:** The flexural MOR and TS are highly sensitive to processing intensity. While a 175 °C treatment preserves or slightly improves strength, severe treatment at 200 °C triggers notable strength degradation, particularly impacting the nodal sections.
- **Compression Enhancement:** Unlike tensile and flexural strength, compression strength increases significantly following thermal modification, leaving all heat-treated specimens superior to their untreated controls.
- **Recommendations for Application:** For structural applications demanding a critical balance of load-bearing capacity and dimensional stability, a moderate treatment of 175 °C for 30 minutes is highly recommended. Conversely, the severe 200 °C treatment should be restricted to non-load-bearing, high-moisture environments where maximum water resistance is prioritized over tensile and flexural performance.

Acknowledgement

The authors would like to express their sincere gratitude to the management and staff of DOST-FPRDI for their support. Special thanks are extended to Engr. Gilberto N. Sapin and the Plywood Unit staff of EPDS for their assistance during laboratory experiments and testing, and to Mr. John Marc Abogador for preparing the methodology illustrations.

Author Contributions

Juanito P. Jimenez Jr.: Conceptualization, Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation; **Michaela Germaine M. Macalinao:** Writing – original draft, Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation.

Funding statement

This research was conducted under the project “**Gluing and Finishing Characteristics of Thermally Modified Bamboo**,” funded by the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (PCAARRD) of the Department of Science and Technology (DOST).

Conflict of interest statement

The authors declare no conflict of interest.

Artificial Intelligence (AI) Disclaimer

The authors explicitly state that no part of this manuscript was drafted or edited using artificial intelligence (AI) tools. The preparation and writing of this article were conducted entirely by the authors.

References

- Alipon, M. A., Bauza, E. B., and Sapin, G. N., (2011), Development of floor tiles from Philippine bamboos, *Philippine Journal of Science*, 140 (1), 33-39.
- ASTM D143-2014. Standard methods of testing small clear specimens of timber. *Annual Book of ASTM Standards*, Section 4, Vol. 04.10, West Conshohocken, PA, USA.
- Awalluddin, D., Mohd Ariffin, M. A., Osman, M. H., Hussin, M. W., Ismail, M. A., Lee, H. S., and Abdul Shukor Lim, N. H., (2017), Mechanical properties of different bamboo species, *MATEC Web of Conferences*, 138, 1-10, <https://doi.org/10.1051/mateconf/201713801024>
- Ba, Z., Luo, H., Guan, J., Luo, J., Gao, J., Wu, S., and Ritchie, R. O., (2023). Robust flexural performance and fracture behavior of TiO₂ decorated densified bamboo as sustainable structural materials, *Nature Communications*, 14 (1), 1234, <https://doi.org/10.1038/s41467-023-36939-6>
- Bui, Q., Grillet, A., and Tran, H., (2017), A bamboo treatment procedure: Effects on the durability and mechanical performance, *Sustainability*, 9 (9), 1444, <https://doi.org/10.3390/su9091444>
- Cermak, P., Rautkari, L., Horacek, P., Saake, B., Rademacher, P., and Sablik, P., (2015). Analysis of dimensional stability of thermally modified wood affected by re-wetting cycles, *BioResources*, 10 (2), 3242-3253, <https://doi.org/10.15376/biores.10.2.3242-3253>
- Finnish Thermowood Association, (2003), *ThermoWood handbook*, Helsinki, Finland. <http://www.thermowood.fi>
- Halip, J. A., Roslan, M. N., Rashid, A. H. A., Seman, N. A. A., Ahmad, N., and Nagasamy, A., (2025), Brief review of bamboo particle-based composites: parameter and performances, *Furniture and Wooden Material Research Journal*, 8(2), 487-499, <https://doi.org/10.33725/mamad.1789197>
- Hill, C., (2006), *Wood modification: Chemical, thermal, and other processes*, John Wiley and Sons, Hoboken, NJ, USA, <https://doi.org/10.1002/0470021748>
- Huang, P., Latif, E., Chang, W. S., Ansell, M., and Lawrence, M., (2017), Water vapour diffusion resistance factor of *Phyllostachys edulis* (Moso bamboo), *Construction and Building Materials*, 141, 216-221, <https://doi.org/10.1016/j.conbuildmat.2017.02.156>
- Iswanto, A. H., Madyaratri, E. W., Hutabarat, N. S., Zunaedi, E. R., Darwis, A., Hidayat, W., Susilowati, A., Adi, D. S., Lubis, M. A. R., Sucipto, T., Fatriasari, W., Antov, P., Savov, V., and Hua, L.S., (2022), Chemical, physical, and mechanical properties of Belangke bamboo (*Gigantochloa pruriens*) and its application as a reinforcing material in particleboard manufacturing, *Polymers*, 14,3111, <https://doi.org/10.3390/polym14153111>
- Jais, F. N. M., Mokeramin, M., Roslan, M. N., Halip, J. A., and Jusoh, W. A. W., (2023), Bamboo fiber for textile applications. In Md Tahir, P., Lee, S. H., Osman Al-Edrus, S. S., and Uyup, M. K. A. (Eds.), *Multifaceted Bamboo: Engineered Products and Other Applications*, 275-290. Springer Nature, Singapore.
- Jimenez J. J. P., Macalinao, M. G. M., and Sapin, G. N., (2021), Physico-mechanical properties of two Philippine bamboos thermally modified in a steam environment, *Philippine Journal of Science*, 150 (1).

- Jimenez, J. J. P., and Ramos, J. E. C., (2024), Dimensional stability and mechanical strength of thermally modified giant bamboo [*Dendrocalamus asper* (Schult.) Backer] using steam and oil, *Advances in Bamboo Science*, 7, 100081, <https://doi.org/10.1016/j.bamboo.2024.100081>
- Jimenez, J. J. P., and Razal, R. A., (2004), Physical and chemical properties of thermally modified Yemane (*Gmelina arborea* R. Br.) wood, *FPRDI Journal*, 30 (1), 89-102.
- Jimenez, J. J. P., and Rizare, M. D., (2024), Physico-mechanical properties and decay fungi resistance of *Dendrocalamus asper* and *Bambusa spinosa* thermally modified in spent engine oil medium. *Advances in Bamboo Science*, 9, 100117, <https://doi.org/10.1016/j.bamboo.2024.100117>
- Li, W., Chen, L., Li, Y., and Li, X., (2020), Bamboo modification with 1,3-dimethylol-4,5-dihydroxyethyleneurea (DMDHEU) catalyzed by maleic anhydride, *Journal of Wood Chemistry and Tech.*, 40 (2), 126-135, <https://doi.org/10.1080/02773813.2019.1697293>
- Liang, Z., Jiang, H., and Tan, Y., (2024), A review of thermal treatment for bamboo and its composites, *Green Processing and Synthesis*, 13 (1), <https://doi.org/10.1515/gps-2023-0263>
- Liese, W., and Tang, T. K. H., (2015), Preservation and drying of bamboo, In Liese, W., and Köhl, M. (Eds.), *Bamboo*, Vol. 10, Springer, Cham, https://doi.org/10.1007/978-3-319-14133-6_9
- Lou, Z., Zheng, Z., Yan, N., Jiang, X., Zhang, X., Chen, S., Xu, R., Liu, C., and Xu, L., (2023), Modification and application of bamboo-based materials: A review—Part II: Application of bamboo-based materials, *Forests*, 14 (11), 2266, <https://doi.org/10.3390/f14112266>
- Mangurai, S. U. N. M., Maulana, S., Murda, R. A., Muhamad, S., Hidayat, W., and Bindar, Y., (2022), Physical and mechanical properties of bamboo oriented strand board under various post-thermal treatment duration, *Jurnal Sylva Lestari*, 10 (3), 310-320, <https://doi.org/10.23960/jsl.v10i3.594>
- Ogunbiyi, M. A., Olawale, S. O., Tudgebe, O. E., and Akinola, S. R., (2015), Comparative analysis of the tensile strength of bamboo and reinforcement steel bars as structural member in building construction, *International Journal of Scientific and Technology Research*, 4 (11), 47-52.
- Pangestu, L. C., Priadi, T., and Prayogo, Y. H., (2026), Resistance to termites and colour change in Gombong bamboo (*Gigantochloa pseudoarundinacea*) modified with boron compounds, vegetable oil, and heating, *Jurnal Sylva Lestari*, 14 (1), 126-144, <https://doi.org/10.23960/jsl.v14i1.1270>
- Ramful, R., and Sakuma, A., (2021), Effect of smoke treatment on flexural strength of bamboo hierarchical structure, *BioResources*, 16 (1), 387-402, <https://doi.org/10.15376/biores.16.1.387-402>
- Ramos, J. E. C., Jimenez J. J. P., and Acda, M. N., (2022). Physico-mechanical properties of arc-laminated giant bamboo using thermally modified segments. *European Journal of Wood and Wood Products*, 80(6), 1367-1375, <https://doi.org/10.1007/s00107-022-01848-w>

- Ramos, J. E. C., and Jimenez, J. J. P., (2025), Enhancing the physico-mechanical properties of Philippine bamboos through spent cooking oil heat treatment, *Journal of Tropical Forest Science*, 37(3), 342-355, <https://doi.org/10.26525/jtfs2025.37.3.342>
- Rao, J., Bao, L., Wang, B., Fan, M., and Feo, L., (2018), Plasma surface modification and bonding enhancement for bamboo composites, *Composites Part B: Engineering*, 138, 157-167, <https://doi.org/10.1016/j.compositesb.2017.11.025>
- Razal, R. A., Dolom, P. C., Palacpac, A. B., Villanueva, M. M. B., Alipon, M. A., Bantayan, R. B., and Malab, S. C., (2012), *Mainstreaming engineered-bamboo products for construction and furniture*, Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development and Forestry Development Center, Philippines.
- Sandberg, D., Kutnar, A., and Mantanis, G., (2017), Wood modification technologies – A review, *iForest*, 10, 895-908, <https://doi.org/10.3832/ifer2380-010>
- Tang, T., Chen, X., Zhang, B., Liu, X., and Fei, B., (2019), Research on the physico-mechanical properties of Moso bamboo with thermal treatment in tung oil and its influencing factors, *Materials*, 12 (4), 599, <https://doi.org/10.3390/ma12040599>
- Wu, J., Zhong, T., Zhang, W., Shi, J., Fei, B., and Chen, H., (2021), Comparison of colors, microstructure, chemical composition and thermal properties of bamboo fibers and parenchyma cells with heat treatment, *Journal of Wood Science*, 67(1), 56. <https://doi.org/10.1186/s10086-021-01988-2>
- Xiao, X., Liang, X., Peng, H., Wang, K., Liu, X., and Li, Y., (2022), Multi-scale evaluation of the effect of thermal modification on chemical components, dimensional stability, and anti-mildew properties of Moso bamboo, *Polymers*, 14 (21), 4677, <https://doi.org/10.3390/polym14214677>
- Yang, X., Huang, Y., Ye, C., Lin, X., Su, N., and Fei, B., (2022), Improving the dimensional stability of round bamboo by environment-friendly modified rosin, *Construction and Building Materials*, 365, 130078, <https://doi.org/10.1016/j.conbuildmat.2022.130078>
- Yu, W., and Wang, Y., (2023), Research on the change in chemical composition and fungal resistance of moso bamboo with heat treatment, *Polymers*, 15(2), 453. <https://doi.org/10.3390/polym15020453>
- Zhang, Y. M., Yu, Y. L., and Yu, W. J., (2012), Effect of thermal treatment on the physical and mechanical properties of *Phyllostachys pubescens* bamboo, *European Journal of Wood and Wood Products*, 71 (1), 61-67, <https://doi.org/10.1007/s00107-012-0643-6>
- Zhang, Y., and Yu, W., (2013), Effect of thermal treatment on the properties of bamboo-based fiber composites, *Scientia Silvae Sinicae*, 49 (5), 160-168, <https://doi.org/10.11707/j.1001-7488.20130521>
- Zheng, Y., Liu, L., Bao, M., Lin, F., Wu, X., Li, Y., Gong, Y., Gu, W., and Zhang, W., (2025), Physical and mechanical properties and microstructure characterization of thermally modified flattened bamboo (*Phyllostachys edulis*) material, *Forests*, 16 (4), 694, <https://doi.org/10.3390/f16040694>
- Zheng, Z., Yan, N., Lou, Z., Jiang, X., Zhang, X., Chen, S., Xu, R., Liu, C., and Xu, L., (2023), Modification and application of bamboo-based materials: A review—Part I: modification methods and mechanisms, *Forests*, 14 (11), 2219, <https://doi.org/10.3390/f14112219>