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Full Length Research Article

Comparative Radial and Axial Variation in the Physical Properties of Bagalunga (*Melia azedarach* L.) and Two Plantation-Grown Wood Species

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ABSTRACT

The wood properties of the tree vary from radial to axial position. Limited local studies focusing on these attributes hinder the improvement of wood applications. This study examined the variation in the physical properties of bagalunga (*Melia azedarach* L.), teak (*Tectona grandis* L.f.) and mahogany (*Swietenia macrophylla* King.) across radial and axial positions. Physical properties were evaluated in accordance with the ASMT D143-2019 standard. Five trees per species were collected in Quezon Province, Philippines. Results showed significant variation in physical properties across species. Bagalunga (161.39%) displayed significantly higher green moisture content (GMC), 57.0% and 43.2% higher than mahogany (89.76%) and teak (104.10%), respectively. In terms of specific gravity (SG), bagalunga (0.42) had the lowest value, while teak (0.56) had the highest. Regarding shrinkage properties, bagalunga recorded the highest tangential and radial shrinkage, which were 49.2% and 48.9% higher than those of teak, and 77.6% and 18.4% higher than those of mahogany, respectively. Along the axial position, volumetric shrinkage (VS) declined from the butt to the middle portion. The VS of bagalunga was stable across axial position, whereas teak and mahogany decreased by 10.3% and 28.6%, respectively. In terms of radial position, a significant decrease in GMC was observed from pith to bark, ranging from 9.46% to 26.99% across species. On the other hand, SG increased towards the bark portion. Bagalunga displayed the highest RS and VS at the bark, while teak showed the lowest. Based on their physical properties, bagalunga, being dimensionally stable, is suited for non-structural applications, while mahogany can be used for structural applications, cabinetry, and furniture, and teak is optimal for high-value products.

1. Introduction

The tropical forest is vital for its high biodiversity (Edwards et al. 2019) and for the wide range of products it produces, such as timber. According to the 2025 Global Forest Resources Assessment (FRA) report launched by the Food and Agriculture Organization of the United Nations (FAO), the world's total forest area is approximately 4.14 billion hectares, representing around 32% of the earth's land area (FAO 2025). Over time, these forests have suffered due to the high demand for wood, as well as the overexploitation of tropical timber forests, with annual losses of 17.6 million hectares per year during the 1990s to 2000s and 10.9 million hectares per year during 2015 to 2025 (FAO 2025). In response, plantation forestry has been implemented in the Philippines (Alipon et al. 2016) and in other tropical countries (Brancalion and Holl 2020; Brancalion et al. 2020) to address the demand for wood supply. With plantation-grown species, the primary economic return comes from the quality of the wood, defined by its moisture content, specific gravity, and stabilized dimensions. These factors all determine durability, processing, and the suitability of the end products.

In the Philippines, the two most commercially important naturalized timbers among plantation species are teak (*Tectona grandis* L.f.) (Pelser et al. 2024; POWO 2025) and mahogany (*Swietenia macrophylla* King.) (Abarquez et al. 2025; Pelser et al. 2023; Telrandhe et al. 2022) owing to their high economic value, durability, and workability. Damanik et al. (2023) stated that teak was known for its exceptional quality and resistance to decay, fungi, and termites. It is also dimensionally stable and can be easily machined. Because of these properties, it is used to make outdoor furniture, boat decks, and for external construction. Mahogany is regarded as the classic timber for cabinet-making; it is prized for its rich red-pink to dark red-brown color, exceptional workability, durability, and fine resistance to rot (Cossid et al. 2025). On the other hand, bagalunga (*Melia azedarach* L.) is one of the fast-growing species that are unfortunately underutilized and are promoted for reforestation and community-based plantations, as in the Philippines and other tropical countries (Aguilos et al. 2020). Its wood is light reddish-brown, coarse-textured, moderately durable against decay but poorly resistant to termites; nonetheless, it is easily worked and commonly used for furniture, plywood, and carvings (Marasigan et al. 2024; Van Duong et al. 2021).

Wood properties and quality vary both between and within species. As a heterogeneous material, wood exhibits radial variation (from pith to bark) and axial variation (from base to top). Industrial processing and exploitation of timber require a good understanding of the unique characteristics of each tree species. The variability of wood is documented in different studies, yet it cannot be fully applied to local species such as bagalunga, teak, and mahogany in Philippine plantations. This is because local conditions are important determinants of wood quality (Gülsoy 2021; Seta et al. 2023), including soil, climate, and silviculture. The critical empirical gap is understanding how local conditions affect the natural variation of timber and the intra-tree variability of the physical properties.

Research has shown radial and axial variations in other species. For instance, Fos et al. (2023) documented radial variation in the anatomical and physical characteristics of *Paulownia elongata* × *P. fortunei* hybrids in Spain, in which properties gradually changed towards the bark. Same variations have been observed in *Acacia mangium* (Nugroho et al. 2012), *M. azedarach* (Van Duong et al. 2021), *Paraserianthes falcataria* (Rahim et al. 2024), and *Pericopsis mooniana* (Anoop et al. 2016). Similarly, Nugroho et al. (2024) reported significant differences in the radial and axial properties of *T. grandis*. They also noted that the bark region had higher density and strength. Most of these studies have shown that from pith to bark, fiber length, cell wall thickness, and more complex vessel structures increase, along with greater density and mechanical strength, which are characteristic of the more mature wood.

Given the Philippines' heavy reliance on plantation-grown timber due to the decline of natural forests and the nationwide logging ban under Executive Order Number 23, series of 2011, a suspension on the cutting and harvesting of timber within natural and residual forest in the country, which established the Anti-Illegal Logging Task Force (Government of the Philippines 2011), a comprehensive understanding of intra-tree variation is essential. Hence, this study aims to address this gap by evaluating the radial and axial variation in green moisture content, specific gravity, and shrinkage properties of bagalunga, teak, and mahogany in a Philippine plantation. The result of this study will provide vital information for both industry and academe to enable more efficient and effective utilization of these species.

2. Materials and Methods

2.1. Raw Materials

The tree samples, namely bagalunga (*Melia azedarach* L.), teak (*Tectona grandis* L.f.), and mahogany (*Swietenia macrophylla* King.) were collected from plantations located in the municipalities of Unisan, San Narciso, and Candelaria in Quezon Province, Philippines (**Fig. 1**). Five (5) trees for each species with a diameter at breast height (DBH) of more than 25 cm were sampled and cut. Tree age, diameter, height, and site condition for each location were documented and presented in **Table 1**.

The DBH was measured at 1.3 m above ground level. From each tree, the butt and middle portions of the stem were determined, with each portion measuring 2.4 m in length. In total, thirty (30) stem segments were obtained, from which a disc 152 mm thick was cut. To evaluate radial variation, each disc was subdivided into four zones from the pith to the bark, namely: near pith, inner intermediate, outer intermediate, and near bark (**Fig. 2**). These discs were prepared for the determination of green moisture content, specific gravity, directional shrinkage, and volumetric shrinkage, following the ASTM D143-52: Standard Test Methods for Small Clear Specimens of Timber (ASTM 2019).

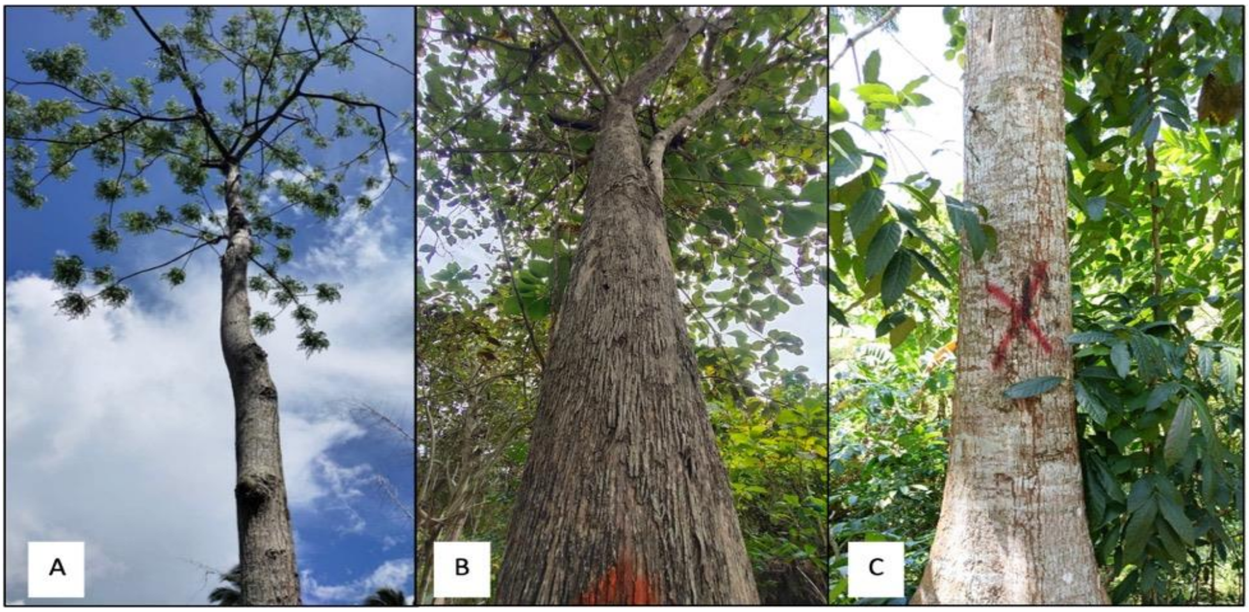
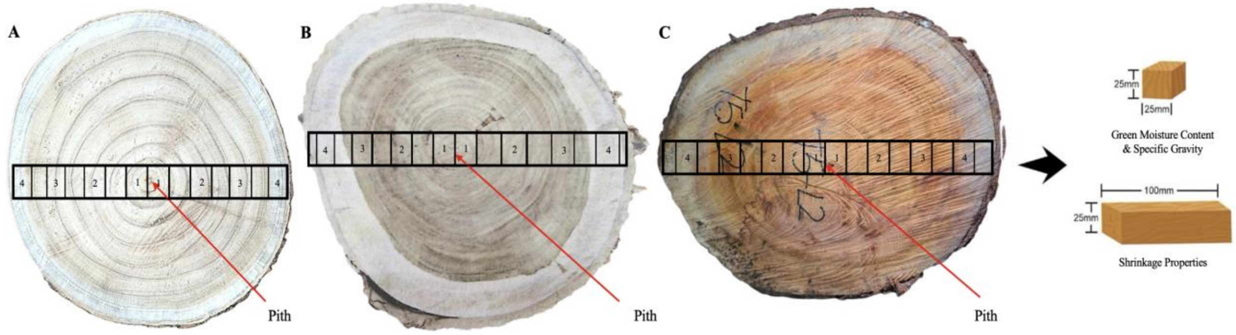


Fig. 1. Photograph of the trees collected for this study: (A) bagalunga, (B) teak, and (C) mahogany.



Radial Zone	Estimated Ring Ranges		
	(A) Bagalunga (~ 10 rings)	(B) Teak (~17 rings)	(C) Mahogany (~14 rings)
1 – Near Pith	1 – 3	1 – 3	1 – 3
2 – Inner intermediate	5	6 – 8	6 – 7
3 – Outer intermediate	7	11 – 13	10 – 11
4 – Near bark	9 – 10	16 – 17	13 – 14

Note: Growth ring boundaries are indistinct, attributed to the poorly defined seasonal variation in the Philippines.

Fig. 2. Sampling scheme used in the study.

Table 1. Characteristics of the collected tree samples and its collection sites

Characteristics	Bagalunga	Teak	Mahogany
Province	Quezon Province	Quezon Province	Quezon Province
Municipality	Unisan	San Narciso	Candelaria
Latitude	13° 49' 22.5" N	13° 33' 21.1" N	13° 59' 03.9" N
Longitude	12° 59' 29.5" E	122° 33' 14.4" E	121° 26' 07.0" E
No. of trees collected	5	5	5
Elevation (masl)	10	160	270
Temperature (°C)	25.67 – 29.33	27.1 – 31.17	26.27 – 30.13
Mean annual rainfall (mm)	243.58	148.25	143.31
Average tree diameter (cm)	26.23	31.34	44.50
Average merchantable height (m)	7.32	7.27	9.60
Estimated tree age (yr)	15 – 25	24 – 26	28 – 30

2.2. Green Moisture Content and Specific Gravity

The green moisture content (GMC) and specific gravity (SG) were determined according to ASTM D143-52 (ASTM 2019). A specimen with dimensions of 25 mm × 25 mm × 25 mm was prepared from each disc. The initial green weight of each specimen was determined using an analytical balance (Shimadzu UX8200S), and its volume was obtained by water displacement. The samples were subsequently oven-dried at 103 ± 2°C until a constant weight was attained, after which the dry weight was measured. GMC was derived from the percentage loss in weight relative to the oven-dry weight, whereas SG was computed as the ratio of oven-dry weight to green volume. A total of 240 specimens (80 per species) were evaluated for these properties, and the values were obtained using Equations 1 and 2.

$$GMC = \left(\frac{W_i - W_o}{W_o}\right) x\ 100 \quad (1)$$

$$SG = \frac{KW_o}{V_w} \quad (2)$$

where *GMC* is the green moisture content from green to oven-dry condition, *SG* is the specific gravity, *Wi* is the initial weight (g), *Wo* is the oven-dry weight (g), *Vw* is the volume of the wood

(cm^3), and K is a conversion constant equivalent to the density of water (1.00 g/cm^3), used since both weight and volume were measured in grams and cubic centimeters.

2.3. Shrinkage Properties

The shrinkage behavior from green to oven-dry conditions was evaluated following ASTM D143-52 using specimens with nominal dimensions of 25 mm (radial) × 25 mm (tangential) × 102 mm (longitudinal). The three principal axes: radial (R), tangential (T), and longitudinal (L), were clearly identified, and dimensional changes were measured using a Mitutoyo digital ABS AOS caliper capable of readings down to 0.0254 mm. For each species, 80 samples were prepared and tested for a total of 240 samples. Directional shrinkage is calculated using Equation 3 as follows.

$$S_a\,(\%) = \frac{Di - Do}{Di} \times 100 \quad (3)$$

where S_a represents shrinkage from green to oven-dry conditions, D_i represents initial dimension (mm), and D_o represents oven-dry dimension (mm).

The difference in specimen volume from the green to the oven-dry condition was used to determine volumetric shrinkage (VS) (Equation 4).

$$V_s\,(\%) = \frac{Vi - Vo}{Vi} \times 100 \quad (4)$$

where V_i is the initial green volume (mm^3), and V_o is the oven-dry volume (mm^3).

2.4. Statistical Analysis

A Factorial in a Complete Randomized Design was used with three factors: species, axial position, and radial position. Before the analysis of variance (ANOVA), the Kolmogorov-Smirnov test showed no significant results ($p > 0.05$), confirming that the data were normally distributed. Analysis of variance (ANOVA) was then conducted to determine the effect of the three factors and their interaction on the wood properties. Tukey's Honestly Significant Difference (HSD) was applied to determine which means differed significantly. Moreover, Pearson correlation analysis was done to assess the association among the properties. All statistical analyses were conducted in Jamovi ver. 2.3 (The Jamovi Project 2023).

3. Results and Discussion

3.1. Green Moisture Content

The statistical summary of the green moisture content for the different species and the ANOVA results are shown in **Table 2**. The results showed significant variation in the GMC across species ($p < 0.0001$). The average GMC of bagalunga was 161.39%, which was significantly higher by 57.04% and 43.15% than those of mahogany (89.76%) and teak (104.10%), respectively. The mean values of GMC, SG, and shrinkage properties of the three species were plotted in a radar chart (**Fig. 3**) to reinforce the trends documented in **Table 2**. On the other hand, along the axial position, no significant differences in GMC were observed ($p = 0.284$).

The results of the present study indicate that bagalunga, with a higher GMC, may require longer drying times than mahogany and teak (Bergman 2021). The observed variation in GMC among species can be partially explained by the negative correlation between GMC and SG (**Fig.**

4), suggesting that compact wood usually retains less moisture. In the present study, bagaluga displayed the lowest SG and highest GMC, while mahogany and teak recorded greater SG but significantly lower GMC.

Table 2. Physical properties across species and axial positions

Species	GMC (%)	SG	Rad (%)	Tan (%)	Long (%)	Vol (%)
Mean Values						
Bagalunga	161.39a	0.42c	4.50a	6.58a	0.25b	10.77a
	(32.71)	(0.06)	(0.89)	(1.52)	(0.19)	(1.81)
Teak	104.10b	0.56a	2.73c	3.98b	0.25b	6.54b
	(20.42)	(0.07)	(2.22)	(0.92)	(0.43)	(2.96)
Mahogany	89.76c	0.50b	3.74b	2.90c	0.46a	6.52b
	(12.38)	(0.06)	(0.92)	(1.71)	(0.40)	(1.23)
Axial Position						
Bagalunga						
Butt	166.63a	0.40a	4.30a	6.62a	0.24a	10.63a
	(35.39)	(0.05)	(0.73)	(1.68)	(0.22)	(1.81)
Middle	156.16a	0.43a	4.70a	6.55a	0.26a	10.90a
	(39.66)	(0.06)	(1.00)	(1.37)	(0.17)	(1.83)
Teak						
Butt	102.99a	0.57a	3.13a	4.53a	0.60a	6.88a
	(22.62)	(0.07)	(2.98)	(2.07)	(0.54)	(3.73)
Middle	105.21a	0.55a	2.33a	3.43a	0.32a	6.20b
	(18.18)	(0.06)	(0.86)	(0.98)	(0.22)	(1.44)
Mahogany						
Butt	92.60a	0.50a	4.11a	2.89a	0.20a	7.46a
	(11.90)	(0.05)	(0.77)	(0.95)	(0.25)	(1.23)
Middle	86.92a	0.51a	3.38a	2.91a	0.31a	5.59b
	(12.35)	(0.06)	(0.93)	(0.91)	(0.50)	(1.14)

Notes: Values are expressed as means, with standard deviations given in parentheses. Means with different superscript letters within a column are significantly different ($p < 0.05$). GMC = Green moisture content; SG = Specific gravity; Rad = Radial shrinkage; Tan = Tangential shrinkage; Long = Longitudinal shrinkage; Vol = Volumetric shrinkage.

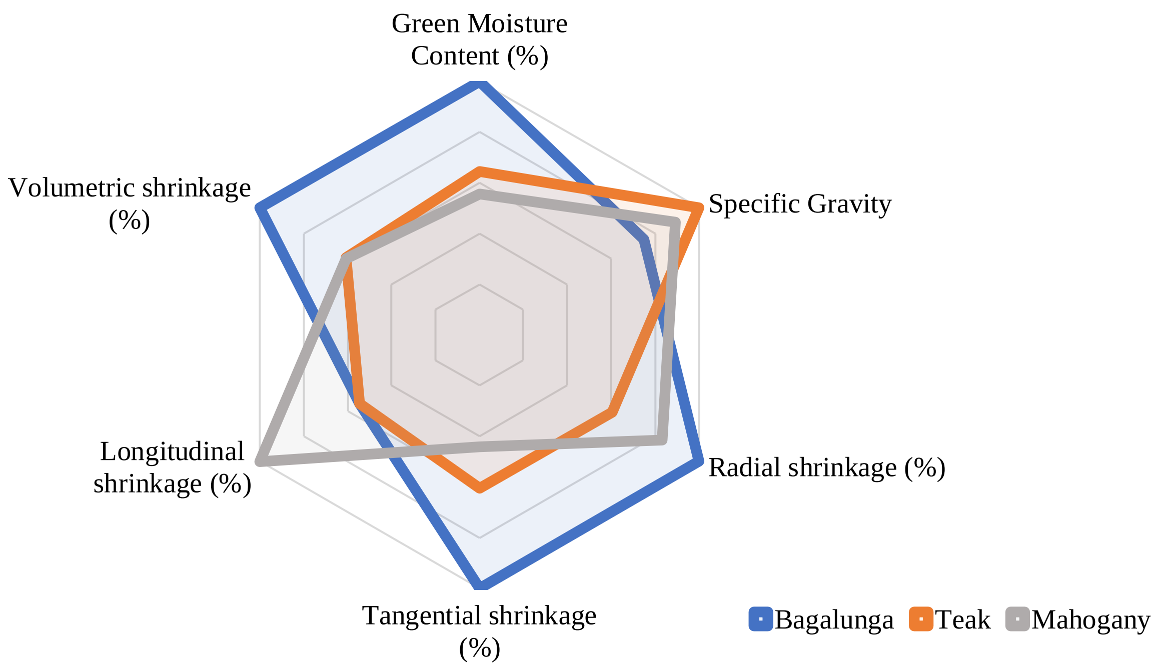


Fig. 3. Radar chart comparing green moisture content, specific gravity, radial shrinkage, tangential shrinkage, longitudinal shrinkage, and volumetric shrinkage of bagalunga, teak, and mahogany.

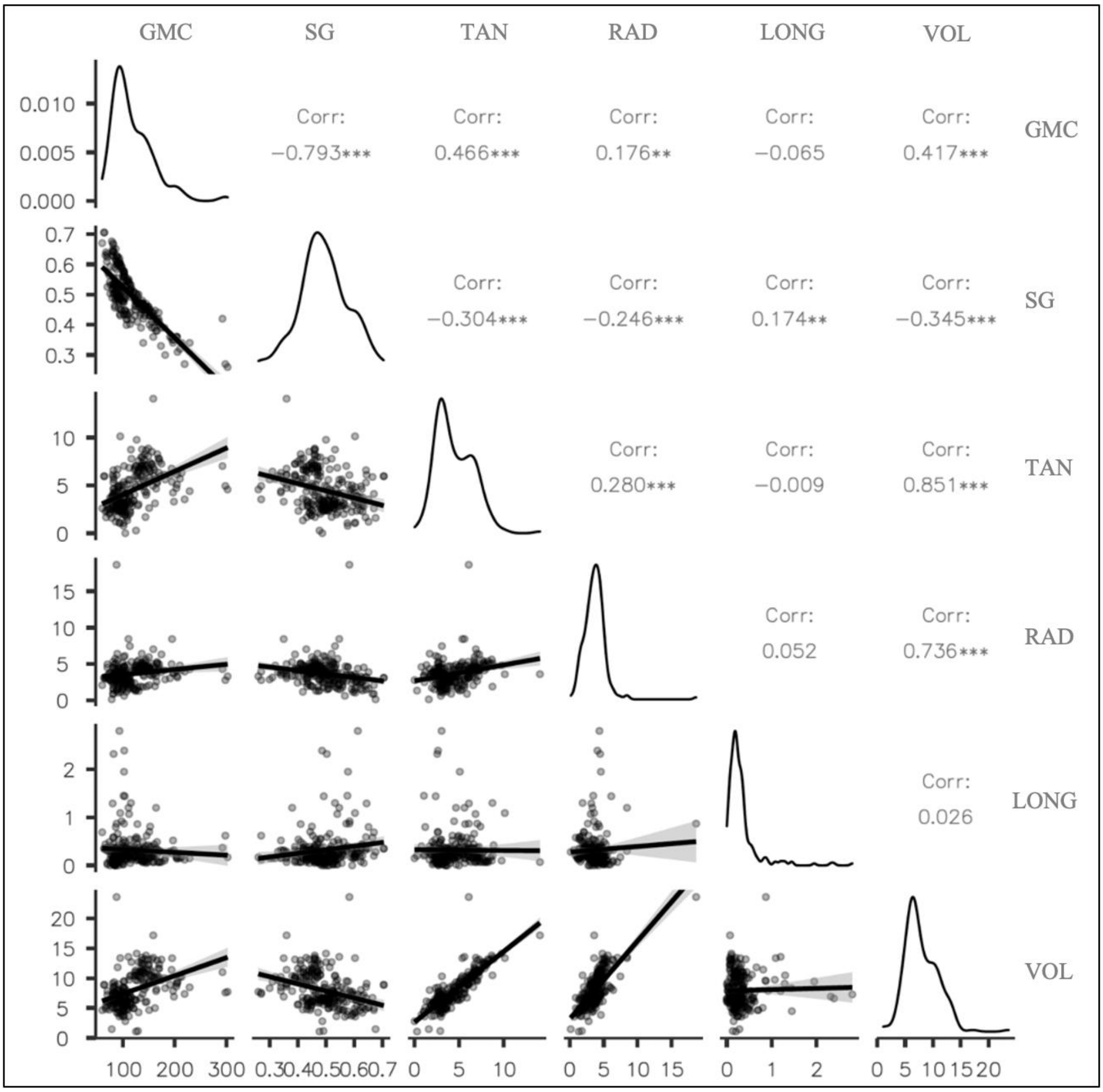


Fig. 4. Correlation analysis of the physical properties of the three plantation species. GMC = Green moisture content; SG = Specific gravity; RAD = Radial shrinkage; TAN = Tangential shrinkage; LONG = Longitudinal shrinkage; VOL = Volumetric shrinkage.

Although variations in GMC were evident across species and positions, the present study did not statistically examine the anatomical and chemical properties that may influence these differences. Therefore, future studies are recommended to assess how these factors affect the moisture behavior of these species. Moreover, the results of the present study indicate that a uniform drying schedule can be applied to both axial positions, as their differences were not significant. This approach may enhance processing efficiency and reduce variability in drying performance.

Across the radial section, significant differences in GMC were observed from pith to bark of the wood (p = < 0.0001). **Fig. 5** illustrates that, for all species, the GMC decreases significantly from the pith to bark in both the butt and middle portions of the stem. Likewise, a decreasing pith-to-bark moisture content (MC) trend is observed in other species, including a 26% decrease in the

P. elongata × *P. fortunei* hybrid (Fos et al. 2023) and a 90% reduction in *P. falcataria* (Rahim et al. 2024).

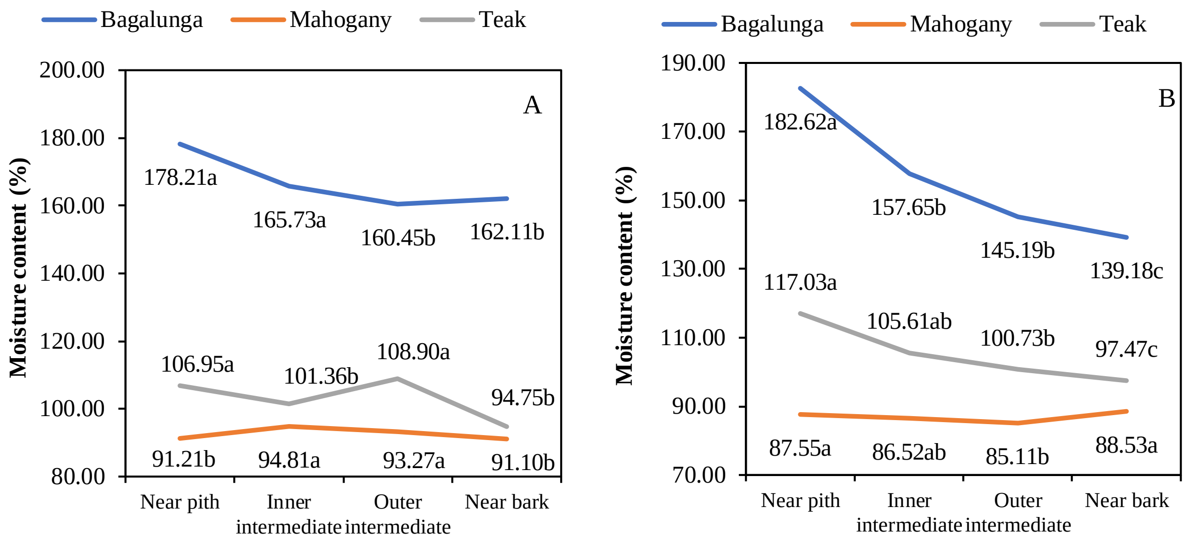


Fig. 5. Radial variation in moisture content of the three species: (A) butt and (B) middle portion.

Wood with a greater MC has more loosely constructed cell walls and more open cells (lumen) which provide additional space for water storage and retention (Glass and Zelinka 2021). In this study, the decrease in GMC from pith to bark across the three species could result from anatomical maturation and changes in macrovessel cell structure. In addition, juvenile wood near the pith still contains significant amounts of capillary water and bound water, which are more pronounced in mature wood due to larger cell lumens and a higher parenchyma ratio (Shmulsky and Jones 2019).

Current findings align with those of Anoop et al. (2016), who found that a higher proportion of parenchyma cells occurs near the pith than near the bark. In contrast, Nugroho et al. (2012) and Van Duong et al. (2021) documented a continuous decline in lumen diameter from pith to bark in *A. mangium* and *M. azedarach*, respectively, suggesting that pith demonstrates greater water-holding capacity. This is supported by Eloy et al. (2024), who found that MC is positively associated with fiber diameter, fiber lumen diameter, and vessel diameter, suggesting that larger cells retain more moisture. In contrast, MC is negatively associated with the fiber cell wall fraction and ray frequency, an association that is more pronounced with aging and has been linked to reduced MC. Additionally, Fos et al. (2023) reported that the very high MC observed in *P. elongata* × *P. fortunei* hybrid wood near the pith was directly related to the low cell wall material content and, consequently, to the high porosity.

Also, the radial maturation of wood, characterized by thicker cell walls and reduced lumen and parenchyma content, naturally explains the declining moisture gradient observed in this study. While anatomical properties were not directly measured in this study, future research could validate their specific relationship with moisture distribution. The present study showed distinct differences in GMC among species, in contrast to findings from other countries. The GMC of bagalunga (161.39%) was lower than that reported for the same species from Iraq, which averaged 208.36% (Abdulqader et al. 2021). On the other hand, the result of the present study in GMC of mahogany (89.76%) was higher compared to samples from Ghana (75.29%) (Apungu et al. 2025).

Similarly, the GMC of teak (104.10%) in the present study was higher than that reported for Malaysian samples (60.83%) (Wahab et al. 2021). These differences can be attributed to variations in environmental conditions, site quality, genetics, and plantation management, which influence wood properties.

3.2. Specific Gravity

Among the species, significant differences in SG were observed (p < 0.001) (**Table 2**). Bagalunga (0.42) displayed significantly lower SG than teak (0.56) and mahogany (0.50). The radar chart highlights differences in SG across species (**Fig. 3**). Bagalunga is positioned at the innermost point, while teak and mahogany are at the outermost and intermediate positions, respectively. On the other hand, along the axial position, no significant differences in SG were observed within each species (p = 0.284).

The significant differences in SG documented across species can be associated with variation in anatomical and chemical properties, as noted for GMC. Van Duong et al. (2021) documented a positive correlation between SG and vessel lumen diameter and cell wall thickness, but a negative correlation with fiber diameter. This indicates that bagalunga may have smaller vessels and thinner fiber cell walls than those of teak and mahogany, which explains its lower SG. Additionally, Van Duong et al. (2021) reported that the average cell fiber wall thickness of bagalunga was 1.41 µm, which was thinner than that of teak (6.1 µm) (Anoop et al. 2014) and mahogany (1.90 µm) (Cardoso et al. 2015). Moreover, Drozdzek et al. (2017) documented a positive association between SG and wood extractives, which might also be an inherited factor affecting SG.

Along the axial position, no significant differences were observed in SG, indicating a lack of notable decrease in mechanical properties along the axial position of the stem. This indicates that the mechanical properties remain consistent from the butt to the middle portion, which is beneficial for structural applications. Regarding SG, bagalunga had a value of 0.42, which is greater than the values reported for samples from Iraq (0.36) (Abdulqader et al. 2021), Saudi Arabia (0.40) (El-Juhany et al. 2011), and Indonesia (0.41) (Praptoyo 2010), but lower than those reported from Mexico (0.55) (Venson et al. 2008) and Malaysia (0.52) (Van Duong et al. 2021). For mahogany, the SG of the present study (0.50) is slightly lower than reported values from India (0.53) (Anoop et al. 2014), the United States (0.64) (França et al. 2024), and Ghana (0.53) (Apungu et al. 2025). Meanwhile, teak in the present study (0.56) showed a higher SG than samples from Indonesia (0.53) (Nugroho et al. 2024), Laos (0.52) (Wanneng et al. 2014), and Malaysia (0.48) (Wahab et al. 2021).

Based on the SG classification by Alipon et al. (2005), bagalunga falls into the moderately low category, while teak and mahogany were classified into the moderately high and medium categories, respectively (**Table 3**). Bagalunga exhibited SG values similar to those of *Shorea almon*, *S. palosapis*, *Eucalyptus deglupta*, and *Hevea brasiliensis*. On the other hand, teak was notably higher than that of the Philippine mahogany group and the most common commercial timber species. In contrast, the SG of mahogany was comparable to species such as *Parashorea malaanonan*, *Shorea negrosensis*, *S. contorta*, *S. polysperma*, *Gmelina arborea*, and *A. mangium*.

Significant increase in SG was observed across the radial section (from pith to bark) in all three species (p < 0.001) (**Table 2**). **Fig. 2** shows the ring number ranges that distinguish the juvenile and mature wood zones, as well as the approximate sapwood to heartwood boundaries. **Fig. 6** further illustrates that, at both axial positions and across all species, SG increased progressively from the pith toward the bark. This trend is consistent with previous findings in various species like *A. mangium* (Nugroho et al. 2012), *S. macrophylla* (40% increase) (Anoop et al. 2014), *Alnus glutinosa* (Kiaei et al. 2016), *P. elongata* × *P. fortunei* hybrid (33% increase) (Fos et al. 2023), *T. grandis* (Nugroho et al. 2024), and *P. falcataria* (Rahim et al. 2024).

Table 3. Specific gravity classification ranges for wood in the green condition (Alipon et al. 2005)

Classification	Range of values	Recommended Uses
Low	≤ 0.36	Light construction where strength, hardness, and durability are not critical requirements, such as door and panel cores, moldings, ceilings, pulp and paper, and core veneer. It can also be used for interior construction, cheap types of furniture, window frames (treated), flooring, planking, and packing cases.
Moderately low	0.37 – 0.44	For pulp and paper production, wood carving and sculpture, conventional furniture, drafting boards, toys,venetian blinds, crates, pallets, form wood, and shingles.
Medium	0.45 – 0.53	General construction, doors, framing, paneling, flooring, planking, medium-grade furniture, cabinets, veneer, and plywood (face and core).
Moderately high	0.54 – 0.66	Medium-heavy construction, such as heavy-duty furniture, cabinets, medium-grade beams, flooring, door panels, frames, tool handles, veneer, and plywood production.
High	≥ 0.67	For heavy-duty construction where both strength and durability are required; also for shipbuilding, railway slippers, paving blocks, tool handles, friction and bearing blocks, pulley sheaves, and rollers, bridge, and wharf timbers, posts, beams, girders, trusses, door, and window sills, balustrades, flooring, and stairs, piles, and poles.

The radial variation in SG observed in the present study can be attributed to differences in anatomical structure. According to Fos et al. (2023), juvenile wood, typically located near the pith, is characterized by lower density and higher porosity, making it less suitable for structural applications where strength and dimensional stability are critical. The present study supports this trend, showing that across species SG increased from pith to bark, indicating a clear tendency toward wood maturation. In terms of mahogany and teak, beyond the outer intermediate zone (**Fig. 6**), the SG stabilized, indicating the emergence of the mature wood portion. On the other hand, the SG of bagalunga steadily increased without reaching a stable state, implying that mature wood may form at later growth stages. This supports the finding that the bagalunga inner portion contains a large amount of juvenile wood, likely of inferior quality.

Fos et al. (2023) also found a positive correlation between SG and both cell wall thickness and cell wall proportion, further emphasizing the relationship between anatomical maturation and increased density. Similarly, Nugroho et al. (2012) found SG in *A. mangium* was more associated with cell wall thickness and fiber wall area, while Van Duong et al. (2021) found SG in *M. azedarach* positively correlated with cell wall thickness and negatively with fiber lumen diameter in the radial direction. Moreover, research beyond the current sampling range is recommended to better clarify the juvenile-to-mature wood transition.

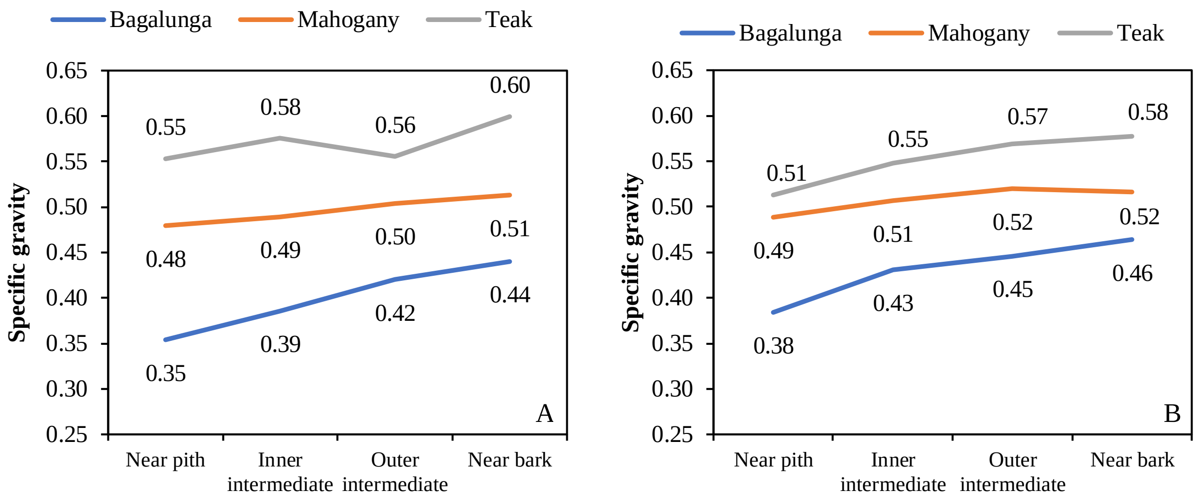


Fig. 6. Radial variation in specific gravity of the three species: (A) butt and (B) middle portion.

3.3. Directional Shrinkage

The directional shrinkage values - tangential (TS), radial (RS), and longitudinal (LS) - for the three species, along with the ANOVA results, are presented in **Table 2**. The analysis showed that species significantly affect shrinkage properties ($p < 0.001$). Bagalunga showed the highest shrinkage in the tangential (6.58%) and radial (4.50%) directions. These values are significantly higher compared to teak (TS: 3.98%, RS: 2.73%) and mahogany (TS: 2.90%, RS: 3.74%). On the other hand, the LS of bagalunga was similar to that of mahogany (0.25%), but significantly lower than that of teak (0.46%). The radar chart (**Fig. 3**) reinforces these variations.

Compared to teak and mahogany, bagalunga TS and RS showed the greatest variation, indicating greater deformation. On the other hand, teak showed a wider range of LS, whereas its RS and TS showed less variation. Regarding mahogany, its directional shrinkage showed a balanced spread. Bagalunga might be prone to warp and cupping during drying due to its high TS and RS. However, this can be minimized through a controlled, slow-drying process (Alipon et al. 2000). While teak is prone to end splits due to its high LS, mahogany demonstrated greater dimensional stability, which is favorable for applications such as cabinetry, paneling, and other high-quality woodworking. Based on the results of the present study, species-specific sawing patterns, cutter allowances, and drying cycles can be developed to minimize various defects and improve the wood yield (Alipon et al. 2000).

A negative relationship was observed between TS, RS, and SG (**Fig. 4**), indicating that species or portions with lower SG exhibit greater shrinkage. This clarifies that bagalunga, exhibiting the lowest SG, presented the highest TS and RS, compared to teak and mahogany, which have high SG and displayed lower shrinkage values. More parenchyma and larger lumen spaces were present in lower-density wood, making it more prone to dimensional changes during moisture loss (Bondad et al. 2022)

Along the axial position, significant differences in TS ($p = 0.03$) and RS ($p = 0.04$) were observed among the species, with all three exhibiting the highest TS and RS values at the butt portion (**Table 2**). The observed differences in shrinkage properties could be attributed to differences in SG along the stem. In all species, the butt portion had lower SG than the middle portion. This association was further reinforced by the negative relationship between SG and both

TS and RS (**Fig. 4**). Moreover, differences in anatomical properties may contribute to this variation. According to Hamdan et al. (2020), shrinkage properties were positively and negatively affected by fiber length and fiber cell wall thickness, and this relationship may be more pronounced in the butt portion. Moreover, a higher microfibril angle (MFA) and lower extractive content, commonly found in juvenile wood near the butt, can also contribute to increased shrinkage (Drozdzek et al. 2017; Shmulsky and Jones 2019). These findings highlight the combined effects of wood density and anatomical composition on shrinkage behavior, suggesting the importance of further investigation into species-specific structural traits.

Radially, no statistically significant differences were found in directional shrinkage (i.e., radial, tangential, and longitudinal) among the species ($p > 0.05$) (**Table 2**). However, species-specific trends were observed (**Fig. 7**). In bagalunga, both RS and TS consistently increased from the pith to the bark. RS rose from 4.14% to 4.51% in the butt and 4.65% to 4.75% in the middle, while TS increased from 6.35% to 7.00% (butt) and 5.41% to 7.51% (middle). Mahogany showed a similar trend in RS, with values increasing from 3.63% to 4.40% in the butt and from 3.01% to 3.86% in the middle, though TS remained relatively stable. On the other hand, a declining pattern in both RS and TS was observed in teak across radial position.

The observed trend in RS in bagalunga and mahogany is consistent with the results of Anoop et al. (2014), Anoop et al. (2016), and Fos et al. (2023), which relate the difference in RS to the development from juvenile to mature wood. Moreover, Fos et al. (2023) stated that the distinct dimensional behavior of wood near the bark reinforced the difference between juvenile wood near the pith and mature wood towards the bark. Anatomical maturation is indicated by increasing shrinkage in bagalunga and mahogany, while teak's declining TS might be due to the presence of mature wood or different growth patterns. In terms of LS, radial decrease was documented in bagalunga, while mahogany displayed a different trend, and teak showed an increasing trend from pith to bark. The observed declining LS in bagalunga was also observed in *P. elongata* × *P. fortunei* (Fos et al. 2023)

3.4. Volumetric Shrinkage

Across species, significant variation in volumetric shrinkage (VS) was observed ($p < 0.001$) and across axial position ($p = 0.005$) (**Table 2**). The VS of bagalunga (10.77%) was significantly higher than those of mahogany (6.54%) and teak (6.52%). The radar chart (**Fig. 3**) reinforced the observed trend, in which bagalunga extended outward, showing that it is dimensionally unstable. On the other hand, teak and mahogany remained close to the center, indicating their low VS values. Moreover, the difference between teak and mahogany was insignificant. Based on the classification of Alipon et al. (2000), the VS of bagalunga was classified as medium shrinkage, with values ranging from 10.6% to 13.2%. In contrast, both mahogany and teak are classified under the low shrinkage category (≤ 7.8%) (**Table 4**).

Along the axial position, significant differences were observed ($p = 0.005$) (**Table 2**). Compared to teak and mahogany, no significant variation was observed between the butt and middle portion of bagalunga, with only a slight increase from 10.63% to 10.90%. Whereas, teak and mahogany displayed significant variation along axial position. In both species, the butt portion showed significantly greater shrinkage than the middle portion.

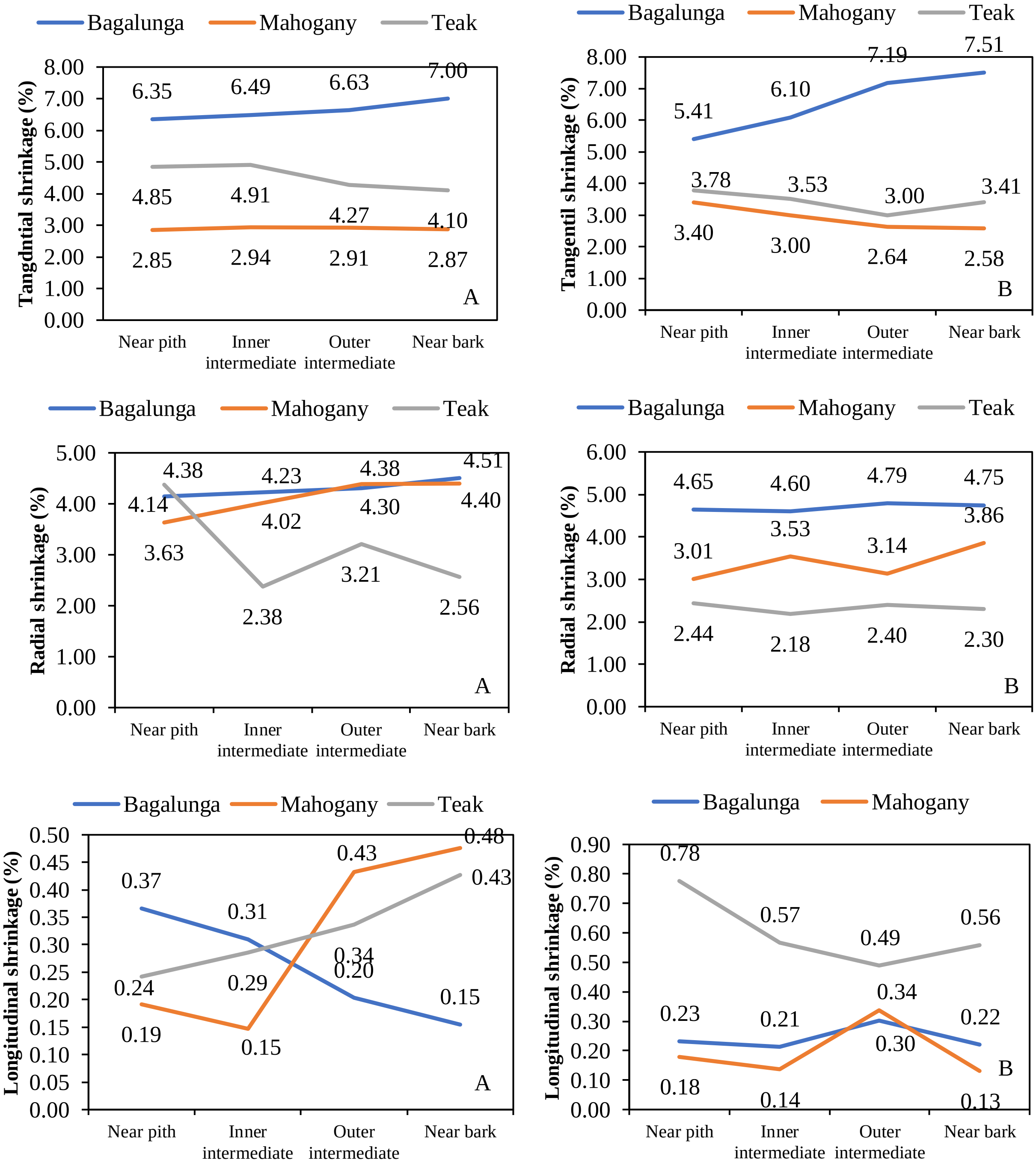


Fig. 7. Radial variation in directional shrinkage of the three species: (A) butt and (b) middle portion.

These axial trends, as well as the differences in VS among species, may be attributed to variations in SG both across species and along the stem height. The observed negative correlation between VS and SG supports this relationship, indicating that species or portions with higher SG tend to exhibit lower VS (**Fig. 4**). For instance, bagalunga, which had the lowest SG (0.42), exhibited the highest shrinkage (10.77%), whereas mahogany (0.50) and teak (0.51) had significantly higher SG values and correspondingly lower VS (6.54% and 6.52%, respectively).

Table 4. Classification of volumetric shrinkage of wood from green to oven-dry conditions (Alipon et al. 2000)

Classification	Range of values(%)	Recommended Uses
Low	≤ 7.8	The most desirable (at least in the Philippines) for high-grade furniture and cabinetry, as well as for other uses where shrinkage is critical, such as mouldings, parquet flooring, musical instruments, tool handles, sporting goods, and others.
Moderately low	7.9 – 10.5	For high-grade to common-grade furniture, and for other uses such as rotary-cut veneer for plywood and related products, house framing, flooring, and ceilings. Also acceptable for millwork/joinery, woodworking, novelties, pickers, and musical instruments.
Medium	10.6 – 13.2	For high-grade furniture, they have good color and finish. Some species may also be good for conventional and ordinary furniture.
Moderately high	13.3 – 16.0	For high-grade furniture, they have good color and finishing characteristics. Moreover, the timber should be dried to the equilibrium moisture content of the locality where it is to be used to obtain satisfactory performance. Also acceptable for millworks/joinery.
High	≥ 16.1	Applications where shrinkage is not of critical importance, such as telegraph poles, mine posts, beams, girders, rafters, chords, and purlins, window sills, balustrades, stairs and highway rail guards, pilings, vehicle spokes and frames, dumb bells, railway sleepers, bearing blocks, pulley sheaves and rollers, bridge, and wharf timbers of telephone.

Although denser woods are generally expected to exhibit greater VS due to the higher proportion of cell wall material, the reverse trend observed in this study may be attributed to species-specific anatomical and chemical characteristics that influence water movement. According to Bondad et al. (2022) and Shmulsky and Jones (2019), increased SG in certain woods is often associated with higher extractive content and tylose formation, which block vessel lumina and reduce permeability. The restriction reduces bound water during drying, resulting in lower shrinkage despite the higher SG. Other structural characteristics, such as fiber wall thickness, ray development, and microfibrillar angle may also affect the shrinkage response (Shmulsky and Jones 2019).

The observed negative correlation between VS and SG (**Fig. 4**), therefore, reflects the combined effects of extractive deposition and reduced water accessibility in denser tissues**,** rather than a purely cell-wall–driven relationship. While these anatomical and chemical features were not quantified in the present study, they represent key factors that can explain the deviation from the conventional positive relationship between specific gravity and shrinkage and warrant further investigation.

No statistically significant differences were found in radial VS from pith to bark, but species-specific trends were observed (**Fig. 8**). The VS of bagalunga increased consistently from pith to bark (butt: 4.14–4.51%; middle: 4.65–4.75%) similar to that of mahogany (butt: 3.63–4.40%; middle: 3.01–3.86%), indicating a maturing and more uniform wood structure toward the outer layers - a trend consitent with the radial increase in SG from pith to bark. In contrast, teak exhibited a decreasing VS trend, declining in the butt (4.38% to 2.56%) and middle (2.44% to 2.30%)

sections. The 5.74% reduction in the middle portion may indicate structural stabilization or a higher proportion of heartwood near the bark.

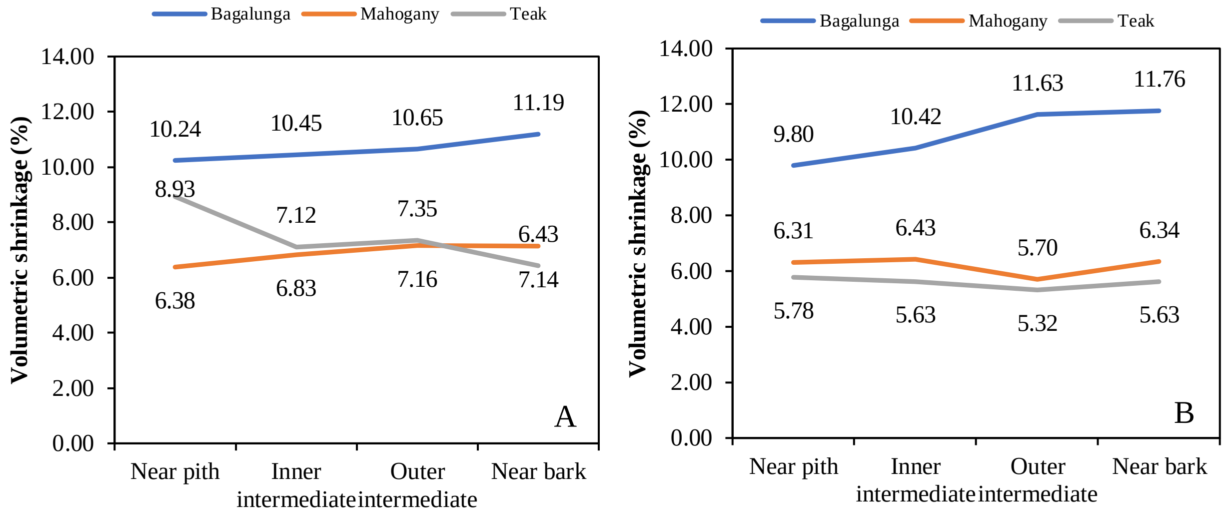


Fig. 8. Radial variation in the volumetric shrinkage of the three species: (A) butt and (B) middle portion.

3.5. Potential Utilization of the Three Plantation Species

The potential application of the three species in the present study was evaluated based on their SG and VS classification, as per Alipon et al. (2000, 2005) (**Tables 3** and **4**). The SG and volumetric shrinkage are widely known parameters used to determine the potential application of various materials. For instance, SG is used as an accurate estimator of wood's mechanical properties, whereas VS indicates its behavior during drying and service.

Bagalunga was classified under moderately low SG and medium VS. This indicates that bagalunga is suitable for light to medium applications. It can be used for products where high strength is not a critical requirement such as crates, pallets, plywood core veneers and conventional furniture. Due to its shrinkage property, it can be used for high-grade furniture, provided appropriate drying is applied. However, it is suggested that bagalunga wood be conditioned to its equilibrium moisture content before fabrication and assembly to ensure product stability.

Mahogany falls into the medium SG and low VS categories. This combination is favorable for products that require strength and stability. Thus, mahogany is recommended for a wide range of general construction applications, such as cabinetry, framing, flooring, doors, and paneling. Moreover, due to its low VS, mahogany may be more stable during drying and service. Also, low VS is essential for applications such as high-grade furniture, fine woodcrafts, and musical instruments. Mahogany, with a medium SG and low VS, combined with its aesthetic appeal and workability, reinforced its status as a high-value material for structural and decorative applications.

The SG and VS of teak felled within the moderately high and low classification, respectively. Due to its high SG and low VS, teak might exhibit higher mechanical properties and stability. Teak is suited for medium- to heavy-duty applications, including flooring, tool handles, window frames, doors, beams, cabinets, and high-quality furniture. It loses VS suggests its potential for high-precision products and high-grade furniture. Teak is also suited for outdoor construction, high-end architectural joinery, and shipbuilding that require resistance to moisture and deformation.

4. Conclusions

The results of the present study indicate that the physical properties of bagalunga were significantly different from those of mahogany and teak at both axial and radial positions. Bagalunga documented the highest GMC and shrinkage, and the lowest SG. Teak, on the other hand, displayed the highest SG and the lowest VS, while mahogany had an intermediate SG and proportional shrinkage in all directions. The variation observed across species can be due to differences in the anatomical and chemical properties. Along the axial position, no significant difference was observed in physical properties except for VS, where it significantly declined towards the middle portion. The VS of bagalunga was stable along the axial position, whereas teak and mahogany decreased by 10.3% and 28.6%, respectively. Across radial position, bagalunga GMC and SG decreased and increased from pith to bark, respectively, similar to that of teak and mahogany. This describes the transition from juvenile to mature wood. Compared to mahogany and teak, which can be used for a wide range of applications such as furniture, cabinetry, paneling, flooring, joinery, and moldings, bagalunga is only suitable for non-structural purposes such as ordinary furniture and carvings (if dried carefully), and as a raw material for pulp and paper. Structural purposes are appropriate for wood from the bark, and low-strength applications are for the wood near the pith. It is recommended that future studies optimize yield and return economically through targeted drying schedules and selective processing, as discussed in this work. Moreover, further studies should explore and assess how local growing conditions, especially soil, climate, and elevation, affect wood property variability to develop more accurate, site-specific utilization recommendations for these plantation species in the country.

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Conflict of Interest

The authors declare no conflict of interest.

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

During the preparation of this work, the authors used Turnitin to detect text similarity and ensure originality of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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