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Physico-Mechanical Properties of Two Native Tree Species in the Philippines and Their Potential as Alternatives to Exotic Industrial Tree Plantation Species

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ABSTRACT

The potential of Bagalunga (*Melia azedarach* L.) and Kalumpit (*Terminalia microcarpa* Decne) as alternatives to Falcata [*Falcataria falcata* (L.) Greuter & R. Rankin], Gmelina (*Gmelina arborea* Roxb. ex Sm.), and Mahogany (*Swietenia macrophylla* King) were evaluated by assessing their physico-mechanical properties in accordance with ASTM D143-52: 2019 standards. Results showed that Mahogany had the lowest green moisture content (MC) at 90.60% and the highest basic relative density (RD_b) at 0.52, while Falcata exhibited the highest green MC (193.98%) and the lowest RD_b (0.29). Bagalunga displayed the highest shrinkage values [tangential shrinkage (TS): 6.63%, radial shrinkage (RS): 4.48%, volumetric shrinkage (VS): 10.81%], whereas Mahogany showed the lowest shrinkage (TS: 3.59%, RS: 3.11%, VS: 6.81%) but the highest longitudinal shrinkage (LS) (0.42%). Mahogany recorded the highest modulus of rupture (MOR) (63.65 MPa and 66.96 MPa at green and 12% MC, respectively), and excelled in compression [parallel (27.28 MPa and 35.62 MPa), perpendicular (7.14 MPa and 7.89 MPa)], hardness [side (4.67 kN and 4.20 kN), end (5.48 kN and 5.49 kN)], and shear strength (8.37 MPa and 10.37 MPa). Kalumpit exhibited the highest toughness in both green and 12% MC conditions (48.51 J/Spec and 42.62 J/Spec), along with the highest SPL (33.42 MPa) and MOE (8.58 GPa) at 12% MC. Gmelina had the highest MOE (7.12 GPa), while Mahogany showed the highest SPL (25.50 MPa) in the green condition. Height levels significantly affected TS and VS, while mechanical properties showed minimal variation. Farmers may consider Bagalunga and Kalumpit as alternative species. The application of silvicultural practices is essential for improving growth, optimizing rotation cycles, and ensuring sustainability for native tree species.

1. INTRODUCTION

The nation's wood industry depends on the best species and management techniques for productive forest plantations that offer farmers the highest possible returns. Forest plantations should aim to optimize volume returns in the shortest rotation period, provided they comply with Executive Order No. 23, which governs logging limitations in natural forests. Due to their ability to grow quickly and reach merchantable sizes in a short time, industrial tree plantation species are favored by farmers (Nath et al., 2016). These species are not endangered in the wild, allowing for harvesting with proper permits and compliance with minor requirements (Marquez et al., 2021). These species are primarily composed of exotic tree species, namely Falcata [*Falcataria falcata* (L.) Greuter & R. Rankin], Mahogany (*Swietenia macrophylla* King), and Gmelina (*Gmelina arborea*

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Roxb. ex Sm.). In 2022, these three species accounted for the highest recorded annual log production volumes, totaling 613,821.88 m^3, 65,870.62 m^3, and 26,599.08 m^3, respectively (DENR-FMB, 2022).

Exotic tree plantations are often criticized for their negative impacts, such as introducing new pests and diseases, affecting native species, and altering both the micro and macro ecosystems of the area (Aguilos et al., 2020). Once established, some exotic species can displace or replace native plant species, disrupt nutrient cycles and biodiversity, and alter plant succession patterns, hastening soil nutrient depletion and affecting long-term site productivity (Marquez et al., 2021).

Native species have historically been outpaced by the widespread introduction of exotic species into plantations since they are considered less productive (Marquez et al., 2021). Nonetheless, interest in fast-growing native species that can sustain biodiversity and replicate natural forest conditions has recently increased due to ecological concerns (Ratsirarson et al., 2002). Furthermore, it has been discovered that native tree plantings are more successful in preserving soil productivity because they promote organic processes such as soil carbon sequestration (Kerdraon et al., 2019).

This study explored the potential of the two native tree species as alternatives to industrial tree plantation species (ITPS) by comparing their physical and mechanical properties. These two species are Bagalunga (*Melia azedarach* L.) and Kalumpit (*Terminalia microcarpa* Decne). Bagalunga was one of the identified fast-growing species of native tree species in the Philippines that can compete with the ITPS (Aguilos et al., 2020). It is a deciduous tree that typically reaches heights of 20-25 m, with a diameter at breast height (dbh) ranging from 40 to 70 cm (Venson et al., 2008).

Kalumpit, a native fruit-bearing tree, is part of the National Greening Program (NGP) of the Philippines. Engay-Gutierez et al. (2023) reported that in 2012, Kalumpit was included in the 862,181 native species produced by the Department of Environment and Natural Resources (DENR) as part of the 3.7 million indigenous planting materials. They also noted that Kalumpit was a priority species for State Universities and Colleges (SUCs) in the Philippines, such as Mariano Marcos State University (MMSU) and Southern Luzon State University (SLSU), and is featured in the NGP demonstration farm.

In the ex-situ performance evaluation of different native tree species in Bohol, Philippines, Kalumpit was one of the top-performing species among the 25 evaluated species, demonstrating exceptional adaptability (Bullecer and Socorin, 2013). Senile and unproductive Kalumpit trees can be used as alternative materials to ITPS (Alipon and Bondad, 2008). It is a semi-deciduous tree that can grow to 25 m in height and has a diameter of 100 cm (Tomas-Carig, 2020).

According to Aguilos et al. (2020), the diameter and height growth rates per year of Bagalunga and Kamlupit were higher compared to the exotic species like *S. macrophylla*, *Schizolobium parahyba*, and *Acacia mangium*. Their results showed that Bagalunga and Kalumpit could potentially grow and survive at a rate close to that of exotic species.

Research on Bagalunga wood has been conducted in several countries. Venson et al. (2008) reported a basic relative density of 0.55 in Mexico, with tangential and radial shrinkage rates of 7.90% and 4.10%, respectively. In China, Vietnam, Malaysia, and Brazil, the basic relative density ranges from 0.34 to 0.47 (Botero, 1956; Pun, 1969; Do Van Ban, 1997). Venson et al. (2008) found its strength similar to *S. macrophylla*, though Alipon and Bondad (2008) reported low strength. Kalumpit has a basic relative density of 0.53 (Reyes et al., 1992) and medium strength (Alipon and Bondad, 2008), suitable for construction, furniture, cabinetry, veneers, and plywood.

The lack of research on the properties of native tree species in comparison with those of exotic species limits the potential of native tree species to promote higher yields and utilization. Hence, this study aims to evaluate the viability of Bagalunga and Kalumpit as sustainable alternatives to exotic ITPS based on their physical and mechanical properties.

2. METHODOLOGY

2.1 Plant materials and wood samples collection

Three trees from each of the following species were collected: Bagalunga (*Melia azedarach* L.), Kalumpit (*Terminalia microcarpa* Dence), Falcata [*Falcataria falcata* (L.) Greuter & R. Rankin], Gmelina (*Gmelina arborea* Roxb. ex Sm.), and Mahogany (*Swietenia macrophylla* King). Descriptions for each species were shown in Table 1. The age of Falcata, Gmelina, and Mahogany represents the recommended age at which farmers utilize these species. The trunks were sectioned into three parts: butt (2.4 m from the base), middle (4.8 m), and top (7.2 m). A total of 45 discs each 152 mm thick, and 45 billets, each 2.4 m long, were cut. The discs were used to assess physical properties, while the billets were used for mechanical properties testing. Figure 1 illustrates the sampling scheme of the study, which was adopted from Alipon et al. (2019).

Table 1. Characteristics of the collection sites and the different tree species

Characteristics	Bagalunga (*Melia azedarach*)	Kalumpit (*Terminalia microcarpa*)	Gmelina (*Gmelina arborea*)	Falcata (*Falcataria falcata*)	Mahogany (*Swietenia macrophylla*)
Region	IV-A	IV-A	XIII	XIII	III
Province	Quezon province	Quezon province	Agusan del Sur	Surigao del Sur	Zambales
Municipality	Unisan	Guinayangan	Baguyan City	Bislig City	Botolan
Barangay	Malvar	Danlangan-Batis	Wawa	Maharlika	San Juan
Number of trees collected	3	3	3	3	3
Elevation (m.a.s.l.)	10.0	71.7	68.5	100.5	26.7
Climatic type	IV	IV	II	II	I
Average tree diameter (cm)	26.23	22.83	24.3	28	20
Average merchantable height (m)	7.32	8.10	9.58	10.33	12.19
Estimated tree age (year)	15-25	15-20	7	7	15

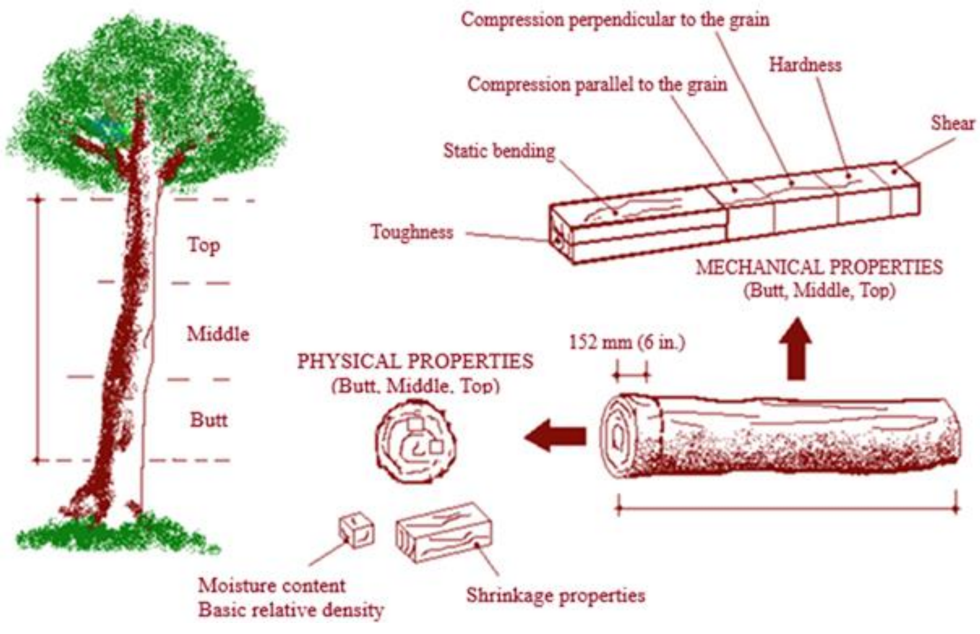

Figure 1. Sampling scheme used in the study (Alipon et al., 2019)

2.2 Determination of physical properties

Physical properties were evaluated using ASTM D143-52: Standard Test Methods for Small Clear Specimens of Timber (ASTM, 2019). A 25 mm × 25 mm × 25 mm sample was cut from the disc to analyze green moisture content (MC) and basic relative density (RD_b). Initially, the sample's weight as recorded, followed by volume measurement using the water displacement method. The samples were then oven-dried at 103±2ºC until they reached a constant weight, after which the oven-dry weight was measured. The green MC was calculated as the percentage loss in weight relative to the oven-dry weight. RD_b was determined by dividing the sample's weight by its volume. In total, 270 samples (54 per species) were tested to assess green MC and RD_b. These were calculated using the following equations:

$$MC\ (\%) = \left(\frac{W_i - W_o}{W_o}\right) \times 100 \quad (1)$$

$$RD_b = \frac{W_o}{V_g} \quad (2)$$

Where; MC: green moisture content, RD_b: basic relative density, W_i: initial weight (g), W_o: oven-dry weight (g), V_g: volume from displaced water (g).

Shrinkage values from green to oven-dry conditions were measured using blocks with dimensions of 25 mm (T) × 25 mm (R) × 102 mm (L). The tangential (T), radial (R), and longitudinal (L) dimensions of each sample were marked and measured with a dial gauge that has a precision of 0.0254 mm. A total of 270 samples, with 54 samples per species, were used to determine the shrinkage properties. The shrinkage properties (i.e., directional, and volumetric shrinkage) were calculated using the following equation:

$$S_a(\%) = \frac{D_i - D_o}{D_i} \times 100 \quad (3)$$

Where; S_a: shrinkage from green to oven-dry conditions, D_i: initial dimension (mm), and D_o: oven-dry dimension (mm).

2.3 Determination of mechanical properties

Mechanical properties were assessed according to ASTM D143-52 (ASTM, 2019). For each species, two sets (18 samples per set) of samples were prepared: green condition and 12% MC. These samples were tested for various properties including static bending [modulus of rupture (MOR), modulus of elasticity (MOE), stress at the proportional limit (SPL)], compression both perpendicular and parallel to the grain, shear strength, hardness (side and end), and toughness. Testing was carried out using the Shimadzu Universal Testing Machine UH-300 kNx series, with loading rates set at 1.3 mm/min for static bending, 0.30 mm/min for compression, 0.6 mm/min for shear, and 6.0 mm/min for hardness.

2.4 Statistical analysis

Statistical analysis was conducted using R Studio version 4.2.1 (R Core Team, 2022). Prior to performing the Analysis of Variance (ANOVA), the Kolmogorov-Smirnov normality test indicated a non-significant result (p=>0.05), suggesting that the data followed a normal distribution. ANOVA was then applied to assess whether there were significant differences in means among species, height levels, and their interactions. To identify which means differed significantly, Tukey's Honestly Significant Difference (HSD) test was employed.

3. RESULTS AND DISCUSSION

3.1 Physical properties

3.1.1 Moisture content and basic relative density

The descriptive statistics (mean, standard deviation, and analysis of variance) for the physical properties of different species at various height levels were presented in Table 2. The ANOVA results indicated statistically significant differences in green moisture content (MC) (p=0.0001) and basic relative density (RD_b) (p=0.0001). A significant interaction between species and height levels was observed in RD_b (p=0.0001), suggesting that this interaction contributed to the variability in this property.

For green MC, Falcata had the highest value at 193.98%, significantly higher than that of the other species, followed by Kalumpit (152.30%), Bagalunga (150.74%), and Gmelina (146.64%). Mahogany had the lowest significant green MC with 90.60%. In terms of RD_b, Mahogany had the highest value at 0.52, significantly higher than that of the other species. Gmelina was the second highest RD_b with 0.44, comparable to Bagalunga (0.43) and Kalumpit (0.42). Falcata, on the other hand, had a significantly lower RD_b of 0.29 compared to the other species.

These results suggested that species with higher green MC, such as Falcata, may require longer drying times. In contrast, Mahogany, having a lower green MC, could dry faster compared to other species. Based on their basic RD_b, Falcata was classified as low-density, while Gmelina, Kalumpit, and Bagalunga were classified as medium density. Mahogany, on the other hand, was classified as moderately high-density (Alipon and Bondad, 2008). These findings suggested that Kalumpit and Bagalunga could potentially be used as alternatives to Gmelina based on their RD_b.

Despite the older age of the Bagalunga compared to Mahogany, it exhibited higher MC and lower RD_b, but it was comparable to that of younger age Gmelina and Kalumpit (Tables 1 and 2). The variation in green MC and RD_b observed among the species can be attributed to differences in their anatomical and chemical properties. Mahogany, for instance, may have thicker cell walls, fewer vessels, and narrower vessel diameters, contributing to its lower MC and higher RD_b (Shmulsky and Jones, 2019).

Table 2. Physical properties of the different species at different height levels

Species	Basic relative density	Green moisture content (%)	Shrinkage properties (%)			
			Tangential	Radial	Longitudinal	Volumetric
Bagalunga	0.43b (±0.05)	150.74b (±20.85)	6.63a (±1.38)	4.48a (±0.97)	0.28b (±0.23)	10.81a (±1.66)
Falcata	0.29c (±0.06)	193.98a (±49.63)	4.41c (±0.81)	2.96d (±0.74)	0.27b (±0.22)	7.23d (±1.09)
Gmelina	0.44b (±0.04)	146.64b (±24.54)	5.16b (±0.96)	3.30c (±0.87)	0.28b (±0.16)	8.3c (±0.94)
Kalumpit	0.42b (±0.04)	152.30b (±19.62)	5.39b (±0.76)	3.76b (±0.61)	0.25b (±0.19)	8.95b (±0.88)
Mahogany	0.52a (±0.05)	90.60c (±13.73)	3.59d (±0.59)	3.11cd (±0.51)	0.42a (±0.50)	6.81d (±0.88)
Height levels						
Butt (2.4 m)	0.42a (±0.06)	148.38a (±30.17)	5.40a (±1.04)	3.45a (±0.95)	0.34a (±0.33)	8.71a (±1.43)
Mid (4.8 m)	0.41a (±0.04)	148.52a (±24.34)	4.87b (±0.85)	3.70a (±0.70)	0.28a (±0.25)	8.43ab (±0.96)
Top (7.2 m)	0.42a (±0.05)	143.65a (±22.51)	4.83b (±0.81)	3.41a (±0.58)	0.28a (±0.20)	8.12b (±0.88)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

No significant differences among the species along the height levels were observed in the green MC ($p=0.156$) and RD_b ($p=0.442$). Regarding green MC, different trends along the height levels were documented. For Falcata, Kalumpit, and Mahogany, an increasing trend towards the top portion was recorded, while a decreasing trend was observed in the other species (Figure 2). Regarding RD_b, an increasing trend towards the top portion was documented in Bagalunga and Mahogany, while a decreasing trend was observed in the remaining species (Figure 3).

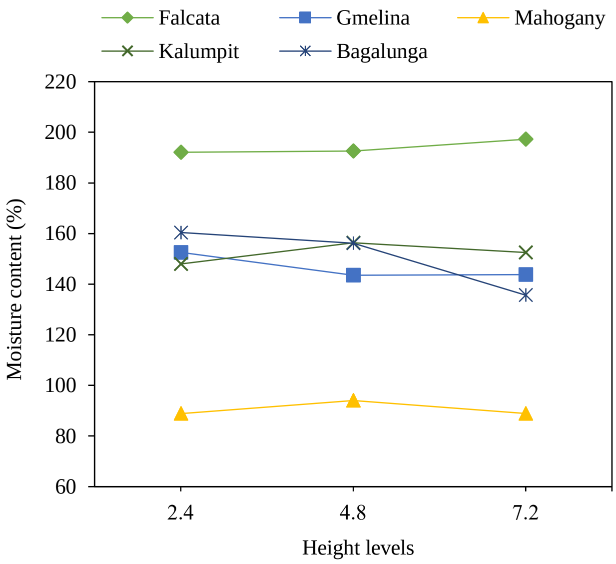

Figure 2. Moisture content along the height levels of the species

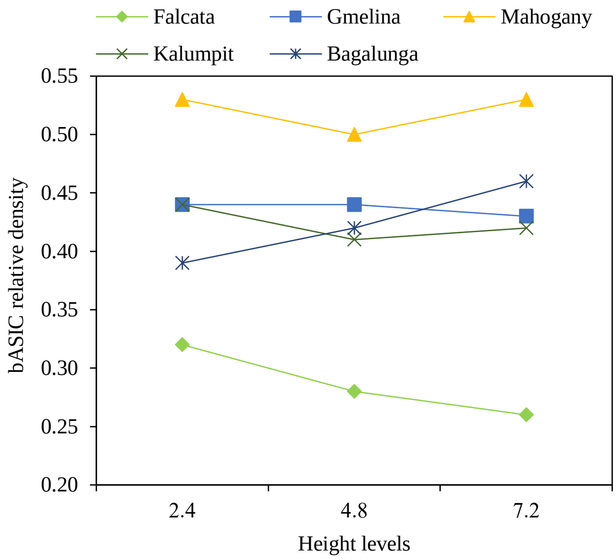

Figure 3. Basic relative density along the height levels of the species

According to Hussin et al. (2014), the variation in green MC along the height levels was due to differences in relative density associated with anatomical properties such as cell wall thickness, vessel diameter, and fiber length. Similarly, the present study observed a negative correlation between MC and RD_b (Table 3). Additionally, Moya et al. (2012) observed the negative effect of these anatomical characteristics on green MC. This finding is supported by Van Duong and Matsumura (2018),

Table 3. Correlation matrix of the physical and mechanical properties.

PROPERTIES	RD	MC	TAN	RAD	LONG	VOL	MOR	MOE	SPL	COMPPAR	COMPPER	SHEAR	SIDE	END
MC	-0.93***	-												
TAN	-0.04	0.19	-											
RAD	0.19	-0.08	0.51***	-										
LONG	0.23*	-0.26*	-0.13	-0.12	-									
VOL	0.1	0.06	0.91***	0.82***	-0.13	-								
MOR	0.77***	-0.71***	-0.1	0.13	0.13	0.01	-							
MOE	0.57***	-0.49***	0.09	0.15	0.1	0.15	0.75***	-						
SPL	0.68***	-0.56***	-0.02	0.15	0.11	0.08	0.78***	0.59***	-					
COMPPAR	0.75***	-0.72***	-0.33**	-0.08	0.14	-0.24*	0.81***	0.55***	0.79***	-				
COMPPER	0.73***	-0.73***	-0.31**	-0.07	0.23*	-0.22*	0.67***	0.40***	0.63***	0.81***	-			
SHEAR	0.81***	-0.76***	-0.12	0.06	0.29**	-0.03	0.77***	0.57***	0.66***	0.67***	0.70***	-		
SIDE	0.79***	-0.77***	-0.30**	-0.12	0.17	-0.23*	0.76***	0.55***	0.73***	0.88***	0.86***	0.78***	-	
END	0.78***	-0.78***	-0.39***	-0.16	0.2	-0.30**	0.73***	0.44***	0.69***	0.88***	0.86***	0.78***	0.93***	-
TOUGHNESS	0.32**	-0.13	0.58***	0.49***	-0.04	0.62***	0.23*	0.23*	0.44***	0.11	0.05	0.15	0.04	-0.02

Note: *p<0.05, **p<0.01, ***p<0.001; RD=relative density, MC=moisture content, TAN=tangential shrinkage, RAD=Radial shrinkage, LONG=longitudinal shrinkage, VOL=Volumetric shrinkage, MOR=Modulus of rupture, MOE=Modulus of elasticity, SPL=stress at the proportional limit, COMPPAR=compression parallel-to-grain, COMPPER=Compression perpendicular-to-grain, END=Hardness: End, SIDE=Hardness: Side who observed a direct relationship between fiber length, cell wall thickness, and relative density in *M. azedarach*. Van Duong et al. (2021) found that the relative density was positively correlated with the diameter of earlywood and latewood vessel lumens, as well as the thickness of earlywood and latewood cell walls. However, it is negatively correlated with the diameter of earlywood and latewood fiber lumens. In a previous study by Van Duong et al. (2018), they reported that the tree with the longest fiber length and low microfibril angle has the highest relative density. Moreover, the proportion of sap, heartwood, earlywood, and latewood deviations along the height levels could also contribute to the variability of MC and RD (Shmulsky and Jones, 2019).

3.1.2 Shrinkage properties

The five species showed significant differences in directional (i.e., tangential, radial, and longitudinal) (p=<0.05) and volumetric shrinkage (p=0.001). Bagalunga exhibited the highest shrinkage values for tangential shrinkage (TS), radial shrinkage (RS), and volumetric shrinkage (VS), with averages of 6.63%, 4.48%, and 10.81%, respectively. In contrast, Mahogany had the lowest shrinkage values for TS, RS, and VS, with averages of 3.59%, 3.11%, and 6.81%, respectively. However, Mahogany exhibited the highest longitudinal shrinkage (LS) at an average of 0.42%, while the other species showed no significant differences in LS.

Based on the classification of Alipon et al. (2005), Bagalunga falls under medium shrinkage, while Gmelina and Kalumpit are categorized as moderately low shrinkage, and Mahogany and Falcata exhibited low shrinkage. The results highlight Bagalunga's susceptibility to drying defects such as checking, warping, and splitting compared to other species, as evidenced by its higher VS values. In contrast, Mahogany shows the lowest tendency for these issues. To address these challenges in Bagalunga, it is crucial to establish an appropriate drying schedule. Based on RD_b, the drying schedule used for Gmelina can be applied for Bagalunga to lessen the occurrence of shrinkage defects (Bergman, 2021). While Kalumpit demonstrated a promising shrinkage property classified under moderately low shrinkage. By considering the TS and RS observed during lumber manufacturing, the study's findings can offer an estimation of a better shrinkage allowance.

A significant effect of the height levels was observed in TS (p=0.000) and VS (p=0.004). In all the species butt portion displayed the highest TS and it decreases towards the top portion (Figure 4). On the other hand, various trend was observed in the VS, for Kalumpit, Gmelina, and Falcata, the butt portion showed the highest VS, and it decreases towards the top portion. For the Mahogany and Bagalunga, the top and middle portions showed the highest VS values, respectively.

The differences in shrinkage properties observed along the height levels could be attributed to differences in the anatomical properties of the trees. According to Hamdan et al. (2020), the shrinkage properties of wood are also positively correlated with the fiber length and fiber cell wall thickness. A high microfibril angle (MFA) and low extractive content can also contribute to the high shrinkage of wood (Drozdzek et al., 2017; Shmulsky and Jones, 2019). The effects of anatomical and chemical properties on the shrinkage properties of these trees can be considered in future studies.

3.2 Mechanical properties

Table 4 presents the mean and analysis of variance obtained for the mechanical properties of the trees under the green and 12% MC conditions. The analysis revealed that the species significantly affected the mechanical properties of the trees under both conditions (p=<0.05). For static bending under green conditions, Mahogany displayed a significantly higher MOR (63.65 MPa) and SPL (25.50 MPa) than other species. Gmelina (50.23 MPa), Bagalunga (48.36 MPa), and Kalumpit (46.16 MPa) exhibited no significant differences in MOR. In terms of SPL, Mahogany (25.50 MPa) exhibited the highest value, followed by Kalumpit (25.24 MPa), and Gmelina (24.64 MPa). While the lowest value was observed in Falcata (11.60 MPa). In terms of MOE, Gmelina (7.12 GPa), Bagalunga (6.72 GPa), and Mahogany (6.64 GPa) displayed significantly higher values than the other species, while Falcata (4.33 GPa) had the lowest values.

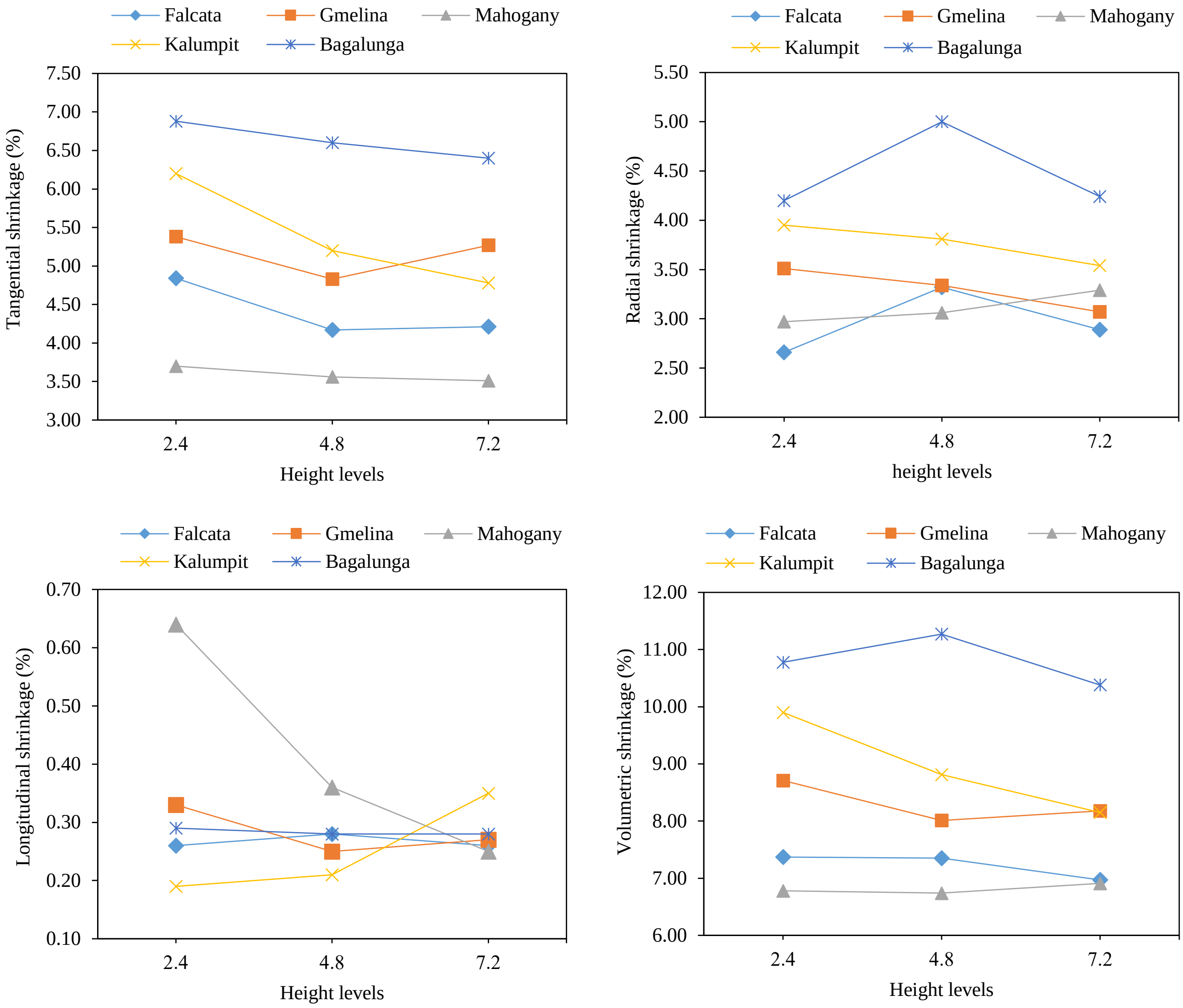

Figure 4. Shrinkage properties along the height levels of the species

Table 4. Mechanical properties at the green and 12% MC condition of the different tree species

Species	Static bending			Compression (MPa)		Hardness (kN)		Shear strength (MPa)	Toughness (J/spec)
	Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Stress at the proportional limit (MPa)	Parallel to the grain	Perpendi-cular to the grain	Side	End		
Green condition									
Bagalunga	48.36b (±7.51)	6.72a (±0.97)	19.60b (±3.90)	15.15c (±2.03)	3.02c (±0.93)	1.97d (±0.39)	2.35d (±0.45)	6.01b (±0.83)	48.51a (±4.85)
Falcata	27.36c (±7.44)	4.33c (±1.29)	11.60c (±4.67)	13.03d (±3.36)	1.94d (±0.70)	1.22e (±0.51)	1.78e (±0.49)	3.03d (±0.68)	13.55d (±4.73)
Gmelina	50.23b (±7.43)	7.12a (±0.78)	24.64a (±3.34)	22.69b (±3.85)	5.10b (±1.74)	3.91b (±0.66)	3.78b (±0.39)	6.45b (±0.79)	36.17b (±10.06)
Kalumpit	46.16b (±6.27)	5.33b (±1.40)	25.24a (±2.28)	22.00b (±2.23)	4.42b (±0.64)	2.68c (±0.35)	3.38c (±0.55)	5.25c (±0.57)	52.73a (±2.34)
Mahogany	63.65a (±8.24)	6.64a (±0.96)	25.50a (±2.88)	27.28a (±1.99)	7.14a (±1.37)	4.67a (±0.45)	5.48a (±0.41)	8.37a (±1.33)	24.20c (±3.97)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

Table 4. Mechanical properties at the green and 12% MC condition of the different tree species (cont.)

Species	Static bending			Compression (MPa)		Hardness (kN)		Shear strength (MPa)	Toughness (J/spec)
	Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Stress at the proportional limit (MPa)	Parallel to the grain	Perpendi-cular to the grain	Side	End		
12% MC condition									
Bagalunga	65.36a (±22.41)	7.34b (±2.23)	21.23b (±12.53)	21.65c (±5.77)	4.79c (±2.52)	2.51c (±1.34)	2.83c (±0.86)	9.20b (±2.09)	42.62a (±15.31)
Falcata	35.46b (±10.81)	4.82c (±1.11)	13.94c (±7.18)	21.56c (±4.49)	2.84d (±1.45)	0.99d (±0.45)	2.24d (±0.69)	4.83e (±0.99)	11.76c (±8.96)
Gmelina	64.72a (±6.98)	6.97b (±1.34)	28.05a (±3.47)	34.80a (±3.00)	4.16c (±1.41)	3.20b (±0.62)	2.87c (±0.52)	6.62d (±1.21)	31.26b (±18.02)
Kalumpit	64.30a (±8.71)	8.58a (±1.96)	33.42a (±6.41)	29.62b (±5.74)	6.53b (±1.09)	2.80bc (±0.50)	3.98b (±0.52)	7.85c (±1.09)	47.43a (±4.15)
Mahogany	66.96a (±7.35)	7.11b (±0.84)	29.69a (±5.50)	35.62a (±4.13)	7.89a (±1.72)	4.20a (±0.82)	5.49a (±0.81)	10.37a (±0.77)	17.90c (±7.27)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

At 12% MC, the MOR of Mahogany (66.96 MPa) displayed the highest value, but was not significantly higher than those of Bagalunga (65.36 MPa), Gmelina (64.72 MPa), and Kalumpit (64.30 MPa), whereas Falcata (35.46 MPa) displayed significantly lower strength. In terms of SPL, Kalumpit displayed the highest value at 33.42 MPa, followed by Mahogany and Gmelina with values of 29.69 MPa and 28.05 MPa, respectively. The differences between these species were not statistically significant. In terms of MOE, Kalumpit (8.58 GPa) had a significantly higher value than the other species. This was followed by Bagalunga (7.34 GPa), Mahogany (7.11 GPa), and Gmelina (6.97 GPa), however, no significant differences were observed among these three species. Falcata had the significantly lowest value at 4.82 GPa.

In terms of compression strength parallel (27.28 MPa) and perpendicular (7.14 MPa) to the grain, shear strength (10.37 MPa), side hardness (4.67 kN), and end hardness (5.48 kN) in the green condition, Mahogany displayed significantly higher values than other species. This was followed by Gmelina and Kalumpit showing comparable values in terms of compressive strength.

At 12% MC, Mahogany exhibited significantly higher values for compression strength both parallel (35.62 MPa) and perpendicular (7.89 MPa) to the grain, shear strength (10.37 MPa), side hardness (4.20 kN), and end hardness (5.49 kN). Kalumpit ranked second in compression perpendicular (6.53 MPa), side hardness (2.80 kN), end hardness (3.98 kN), and shear strength (47.43 MPa), while Gmelina followed in compression parallel (34.80 MPa) and side hardness (3.20 kN). Both in the green and 12% MC conditions, Falcata had the lowest strength values across all properties. However, Bagalunga and Kalumpit displayed significantly higher toughness strengths than ITPS.

Despite its older age, Bagalunga displayed lower mechanical properties than Mahogany, though it showed comparable strength to younger Gmelina and Kalumpit. In contrast, the higher mechanical properties demonstrated by Mahogany under various conditions can be attributed to its RD. As shown in Table 2 and Table 3, the RD_b of Mahogany was significantly higher than those of other tree species and was positively correlated with the strength properties, respectively.

Similar findings were also documented by Hamdan et al. (2020) and Nordahlia et al. (2014) in *F. falcata*, *Balakata baccata*, *Macaranga gigantea*, *Endospermum diadenum*, and *Azadirachta excelsa*, respectively. Other studies have also reported that the mechanical properties of wood are significantly affected by fiber length, fiber wall thickness, and vessel diameter (Nordahlia et al., 2014; Hamdan et al., 2020). However, the effects of these factors were not explored in the present study and present an interesting opportunity for future research.

The mechanical properties of the trees in this study generally increased in strength as they were conditioned from green to 12% MC, except for toughness (Figure 5), while some species also exhibited reductions in hardness. Bagalunga displayed the highest overall average increase in mechanical properties averaging 50.23%, followed by Kalumpit (30.75%) and Falcata (25.12%), while the lowest was observed in Mahogany (6.41%) and Gmelina (2.48%). The increase in strength can be attributed to the shortening and strengthening of hydrogen bonds between the microfibrils, resulting in enhanced mechanical properties (Desch and Dinwoodie, 1996). However, the decrease in toughness can be attributed to the decrease in MC, which makes the wood brittle (Shmulsky and Jones, 2019).

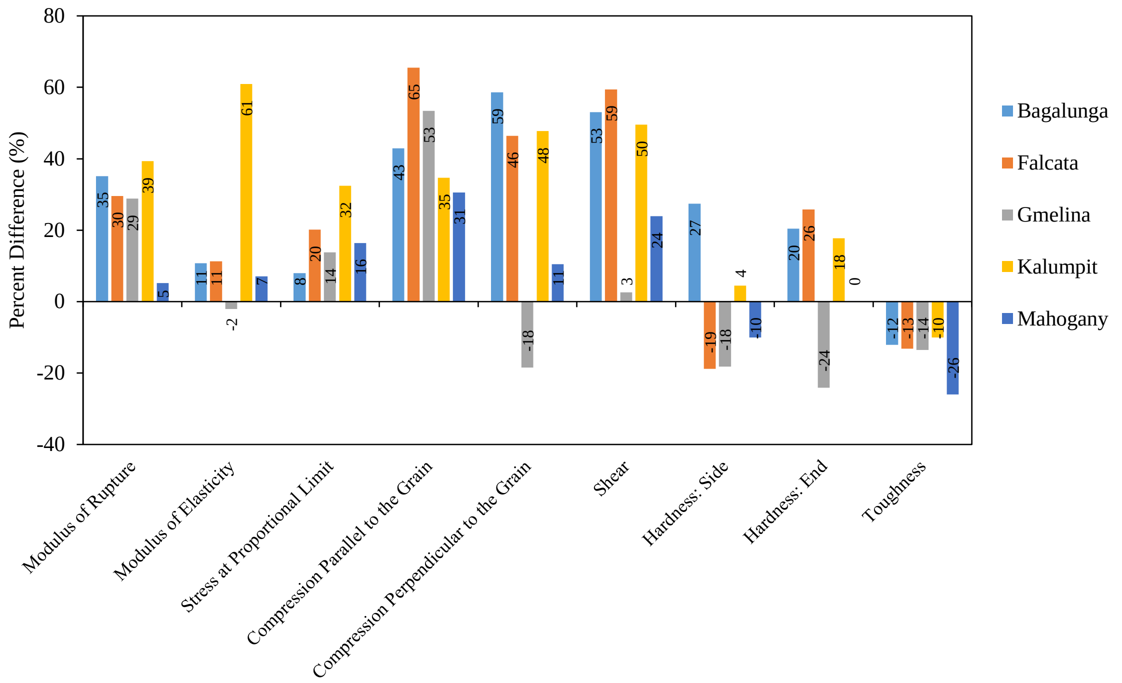

Figure 5. Percent difference in mechanical properties of different species after conditioning from green to 12% MC condition

Based on the classification of Alipon and Bondad (2008), Mahogany was classified under moderately high strength, Bagalunga, Kalumpit, and Gmelina under medium strength, and Falcata under low strength. The recommended uses for these species are listed in Table 5. The results of the study indicated that Bagalunga and Kalumpit can be used as alternatives to Gmelina, consistent with the recommendations of Natividad (2016) and Venson et al. (2008).

Table 5. Strength classification of native and industrial tree plantation species and their recommendations

Strength classification*	Species	Recommended uses*
Moderately high	Mahogany (*Swietenia macrophylla*)	Medium-heavy construction such as heavy-duty furniture, cabinets, medium-grade beams, flooring, door panels, frames, tool handle, veneer, and plywood production
Medium	Bagalunga (*Melia azedarach*) Gmelina (*Gmelina arborea*) Kalumpit (*Terminalia microcarpa*)	General construction, doors, framing, paneling, flooring, planking, medium-grade furniture, cabinet, veneer, and plywood (face and core).
Low	Falcata (*Falcataria falcata*)	Light construction where strength hardness and durability are not critical requirements such as door and panel cores, moldings, ceiling, 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.

Source: *Alipon and Bondad (2008)

Along the height levels, significant variations in mechanical properties across species under both green and 12% MC conditions were observed (Tables 6 and 7). In the green condition, significant differences in toughness were observed along the height levels ($p=<0.001$). The interaction of species × height levels was significant for MOR ($p=0.007$). Tukey's HSD test revealed that the MOR of the middle portion of the Kalumpit was significantly higher than that of the top portion, while the toughness of the butt portion of the Gmelina was significantly higher than those of the other portions.

In the 12% MC condition, the interaction of species × height levels showed significant differences in MOR ($p=<0.001$), MOE ($p=0.003$), compression parallel to the grain ($p=0.004$), shear strength ($p=0.000$), and hardness (end) ($p=<0.001$). Tukey's HSD revealed that the MOR and shear strength of the top portion of Bagalunga were significantly higher than those of the butt and middle portions. The top and butt portions of the Bagalunga and Kalumpit, on the other hand, showed significantly higher compression parallel to the grain than the other portions. In terms of end hardness, the Kalumpit top portion displayed significantly lower strength than the butt and middle portions. The variations in the mechanical properties between different height levels can be attributed to the differences in RD_b (Figure 3 and Table 3). Similar observations have been reported in other species, such as *F. falcata* (Marasigan et al., 2022), *Eucalyptus gomphocephala*, *E. cladocalyx*, and *E. grandis* × *camaldulensis* (Wessels et al., 2016), where the sections with the highest RD exhibited the highest mechanical properties.

Table 6. Mechanical properties at the green condition at different height levels

Species	Height levels	Static bending			Compression (MPa)		Hardness (kN)		Shear strength (MPa)	Toughness (J/spec)
		Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Stress at the proportional limit (MPa)	Parallel to the grain	Perpendicular to the grain	Side	End		
Bagalunga	Butt	43.33a (±3.84)	5.92a (±0.74)	19.44a (±2.60)	14.23a (±1.09)	2.98a (±0.84)	1.83a (±0.32)	2.26a (±0.30)	5.58a (±0.58)	50.84a (±3.62)
	Mid	52.23a (±4.99)	6.75a (±0.91)	21.25a (±2.16)	16.56a (±1.80)	2.56a (±1.17)	1.99a (±0.49)	2.35a (±0.50)	6.17a (±0.78)	46.47a (±6.59)
	Top	49.53a (±13.70)	7.51a (±1.28)	18.12a (±6.96)	14.66a (±3.19)	3.50a (±0.78)	2.09a (±0.35)	2.45a (±0.54)	6.28a (±1.14)	48.21a (±4.33)
Falcata	Butt	28.87a (±10.75)	4.23a (±1.69)	11.47a (±6.23)	12.95a (±4.40)	2.09a (±0.94)	1.43a (±0.50)	1.75a (±0.46)	3.09a (±0.58)	14.38a (±5.37)
	Mid	27.64a (±7.35)	4.41a (±1.47)	11.93a (±6.58)	13.64a (±3.77)	2.14a (±0.77)	1.31a (±0.60)	1.90a (±0.65)	3.11a (±0.92)	14.35a (±5.77)
	Top	25.56a (±4.21)	4.35a (±0.70)	11.41a (±1.20)	12.49a (±1.91)	1.59a (±0.40)	0.92a (±0.44)	1.69a (±0.36)	2.90a (±0.53)	11.92a (±3.04)
Gmelina	Butt	50.36a (±6.94)	7.63a (±0.86)	25.91a (±4.22)	23.10a (±2.04)	5.35a (±2.11)	4.26a (±0.65)	4.00a (±0.53)	6.26a (±0.89)	42.02a (±12.31)
	Mid	55.05a (±8.23)	7.71a (±0.68)	25.77a (±3.37)	22.96a (±4.06)	5.65a (±2.32)	4.04a (±0.83)	3.77a (±0.29)	6.70a (±0.67)	33.28b (±5.35)
	Top	45.28a (±7.11)	6.02a (±0.79)	22.25a (±2.41)	22.00a (±5.46)	4.30a (±0.80)	3.44a (±0.51)	3.58a (±0.35)	6.38a (±0.80)	33.20b (±12.53)
Kalumpit	Butt	48.66ab (±8.15)	4.92a (±1.60)	26.13a (±2.94)	21.73a (±2.69)	4.46a (±0.70)	2.88a (±0.32)	3.55a (±0.60)	5.70a (±0.60)	51.58a (±4.93)
	Mid	53.04a (±1.99)	5.81a (±1.15)	25.55a (±3.78)	23.13a (±2.12)	4.72a (±0.49)	2.79a (±0.44)	3.41a (±0.33)	5.51a (±0.82)	51.53a (±1.42)
	Top	36.79b (±8.67)	5.27a (±1.46)	24.05a (±0.11)	21.14a (±1.90)	4.07a (±0.72)	2.35a (±0.29)	3.19a (±0.73)	4.52a (±0.29)	55.07a (±0.68)
Mahogany	Butt	63.80a (±5.70)	6.77a (±0.69)	28.27a (±2.13)	27.59a (±0.63)	7.00a (±0.80)	4.66a (±0.44)	5.47a (±0.39)	8.89a (±0.77)	28.86a (±3.17)
	Mid	58.41a (±12.04)	6.27a (±1.36)	23.32a (±2.14)	24.96a (±3.52)	7.49a (±2.56)	4.51a (±0.68)	5.73a (±0.38)	8.77a (±0.53)	20.70a (±5.49)
	Top	68.74a (±6.98)	6.88a (±0.83)	24.92a (±4.36)	29.30a (±1.80)	6.93a (±0.76)	4.85a (±0.22)	5.25a (±0.45)	7.44a (±2.68)	23.04a (±3.26)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

Table 7. Mechanical properties at 12% MC condition at different height levels

Species	Height levels	Static bending			Compression (MPa)		Hardness (kN)		Shear strength (MPa)	Toughness (J/spec)
		Modulus of rupture (MPa)	Modulus of elasticity (GPa)	Stress at the proportional limit (MPa)	Parallel to the grain	Perpendicular to the grain	Side	End		
Bagalunga	Butt	49.40b (±24.52)	6.09a (±2.28)	15.70a (±11.34)	17.65b (±6.54)	4.67a (±2.74)	1.75a (±1.34)	2.09a (±0.95)	7.40b (±2.83)	47.63a (±9.77)
	Mid	56.86b (±29.06)	7.72a (±2.98)	18.45a (±10.82)	19.57b (±8.69)	4.28a (±2.30)	2.79a (±1.62)	3.01a (±0.71)	9.14b (±2.43)	44.39a (±11.08)
	Top	89.82a (±13.64)	8.22a (±1.42)	29.54a (±15.43)	27.72a (±2.07)	5.42a (±2.52)	2.98a (±1.05)	3.39a (±0.93)	11.07a (±1.02)	35.84a (±25.07)
Falcata	Butt	35.17a (±13.69)	4.97a (±1.37)	11.67a (±8.12)	24.54a (±7.25)	3.55a (±1.70)	1.15a (±0.57)	2.62a (±1.00)	4.88a (±1.70)	14.56a (±12.82)
	Mid	35.33a (±12.50)	4.70a (±1.13)	15.05a (±7.62)	18.94a (±3.31)	2.32a (±1.68)	0.81a (±0.39)	2.07a (±0.36)	4.87a (±0.52)	12.27a (±10.51)
	Top	35.88a (±6.22)	4.79a (±0.83)	15.10a (±5.80)	21.19a (±2.91)	2.66a (±0.95)	1.01a (±0.38)	2.03a (±0.70)	4.74a (±0.74)	8.44a (±3.53)
Gmelina	Butt	68.50a (±7.05)	5.71a (±2.60)	29.93a (±5.35)	37.16a (±3.05)	4.78a (±2.11)	3.91a (±0.54)	3.35a (±0.57)	7.62a (±0.82)	37.45a (±26.20)
	Mid	59.26a (±11.06)	6.47 (±0.64)	25.21a (±2.82)	32.96a (±3.59)	4.45a (±0.78)	2.77a (±0.71)	2.59a (±0.64)	5.90a (±1.97)	30.38a (±19.59)
	Top	66.39a (±2.83)	8.74a (±0.79)	28.99a (±2.24)	34.28a (±2.37)	3.26a (±1.33)	2.93a (±0.60)	2.65a (±0.35)	6.33a (±0.84)	25.94a (±8.27)
Kalumpit	Butt	67.42a (±11.98)	10.22a (±3.09)	38.73a (±5.80)	32.76a (±6.24)	7.61a (±0.92)	3.32a (±0.73)	4.57a (±0.52)	8.58a (±0.67)	45.98a (±2.20)
	Mid	72.50a (±7.40)	8.46a (±1.62)	34.33a (±6.14)	29.85ab (±5.45)	6.60a (±0.85)	2.99a (±0.47)	4.40a (±0.59)	8.04a (±0.85)	44.46a (±6.90)
	Top	52.98a (±6.75)	7.07a (±1.18)	27.20a (±7.30)	26.25b (±5.52)	5.37a (±1.48)	2.10a (±0.30)	2.98b (±0.46)	6.92a (±1.75)	51.85a (±3.36)
Mahogany	Butt	63.99a (±10.00)	6.86a (±1.24)	34.06a (±4.89)	34.12a (±3.51)	7.38a (±2.37)	4.28a (±0.87)	5.16a (±0.97)	9.56a (±0.69)	20.23a (±8.48)
	Mid	70.35a (±3.50)	7.63a (±0.52)	28.82a (±6.51)	37.91a (±1.87)	8.38a (±1.95)	3.94a (±0.85)	5.29a (±0.84)	10.49a (±0.59)	16.45a (±4.69)
	Top	66.55a (±8.55)	6.85a (±0.76)	26.21a (±5.11)	34.83a (±7.03)	7.90a (±0.83)	4.39a (±0.75)	6.01a (±0.61)	11.06a (±1.04)	17.03a (±8.64)

Note: Values in parentheses represent the standard deviation. Means sharing the same letter within a column are not significantly different. Letters (a-d) denote values from highest to lowest.

Anatomical properties, such as fiber cell wall thickness, fiber length, vessel frequency, and diameter, may also account for the differences in strength properties across the height levels (Lundqvist et al., 2017). In addition, Nasser et al. (2010) reported that the mechanical features of *M. azedarach*, such as MOR, MOE, compression strength, and hardness, are positively correlated with the extractive content. Their study revealed that extractives reinforce cell walls and improve the mechanical properties of wood. In the case of *A. mangium*, the extractive content increased from the butt to the top (Amini et al., 2017).

4. CONCLUSION

Bagalunga and Kalumpit are viable alternatives to exotic industrial plantation species in the Philippines. Bagalunga exhibits characteristics suitable for plantation development, including a relatively straight bole, large diameter, high merchantable height, and fast growth. Kalumpit, primarily cultivated for its fruit, also features a straight bole, large diameter, and high adaptability. The physical and mechanical properties of Bagalunga and Kalumpit were comparable to Gmelina and Mahogany and higher than those of Falcata. Their MC and RD_b values were similar to Gmelina, with Bagalunga showing the highest shrinkage, classifying it under the medium category, while Kalumpit exhibited moderately low shrinkage, similar to Gmelina. The mechanical properties of both species fell under the medium-strength, making them suitable for general construction applications such as doors, flooring, furniture, and plywood veneer. Both species also demonstrated a significant increase in strength after conditioning to 12% MC.

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DECLARATION OF COMPETING INTERESTS

The authors declare no conflict of interest.

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