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Effects of Tree Spacing on the Physical and Mechanical Properties of 24-Year-Old *Tectona grandis* Wood in Longuza Forest Plantation, Tanzania

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ABSTRACT

This study investigated the effects of initial tree spacing on the physical and mechanical properties of 24-year-old teak (*Tectona grandis*) in Longuza Forest Plantation, Tanzania. Three spacing treatments (2 m × 2 m, 3 m × 3 m, and 4 m × 4 m) were evaluated using a randomized complete block design with three replications. Physical properties assessed included wood density (D) and heartwood percentage (HWP), while mechanical properties comprised modulus of elasticity (MOE), modulus of rupture (MOR), compressive strength parallel to the grain (CSP), shear strength parallel to the grain (SS), and cleavage strength (CLS). Results showed that spacing had no significant effect ($p > 0.05$) on most physical and mechanical properties, except for SS and tangential CLS at specific height levels. Although non-significant, D, MOE, MOR, CSP, and CLS tended to decrease with increasing spacing, whereas HWP and SS exhibited variable trends. The highest mean values for D (0.57 g/cm^3), MOE (8,588 N/mm^2), MOR (90.78 N/mm^2), CSP (49.41 N/mm^2), and CLS (14.83 N/mm) were observed at a 2 m × 2 m spacing, while the lowest values generally occurred at the widest spacing (4 m × 4 m). The findings suggest that closer spacing may enhance wood quality by promoting higher wood density and strength, although differences were not statistically significant. These results provide insights for silvicultural management of *T. grandis* plantations, suggesting that a 2 m × 2 m spacing may be preferable for optimizing physical and mechanical wood properties at older stand age.

1. Introduction

Wood properties are a major factor to consider as they influence the quality of the final harvest of teak (*Tectona grandis*) wood. For instance, *T. grandis* wood harvested at 40 years has greater wood density and higher heatwood compared to that of 10 years (Rizanti et al. 2018). *T. grandis* wood has been used in various ways, including heavy construction, furniture and cabinets, railway sleepers, decorative veneers, joinery, and shipbuilding (Thulasidas and Bhat 2012). This is attributed to its excellent physical and mechanical properties. Regarding wood quality, wood density and heartwood percentage are two key properties that affect the quality of *T. grandis* wood. Wood density is used as an index of wood substances, including latewood content, wall thickness, cell size, the number of ray cells, and the size and quantity of vessel elements (Sinha et al. 2017). Subsequently, those wood substances affect the wood's strength, especially its mechanical properties. In addition, the high natural durability of *T. grandis* is attributed to the chemical composition of its heartwood (Damanik et al. 2023; Rodríguez-Anda et al. 2019).

In Tanzania, Technical Order Number 1 of 2021 specifies the spacings of 2.5 m × 2.5 m and 3 m × 3 m that must be used in forest plantations growing *T. grandis* wood (FBD 2021). Spacing is a silvicultural tool that can be used to ensure the quality of final harvests by influencing the growth rate and morphology of individual trees, which in turn affects wood properties (Hébert et al. 2016). For example, spacing affects the heartwood percentage through its influence on radial growth. Heartwood percentage is associated with tree size. Thus, spacing that ensures higher radial growth may produce valuable wood in terms of heartwood percentage. Zahabu et al. (2015) observed the highest heartwood percentage at a wider spacing of 4 m × 4 m, which also produced trees with higher diameters at breast height (DBH). Furthermore, the results showed that the spacings of 2 m × 2 m and 3 m × 3 m had higher wood density compared to 4 m × 4 m spacing. This is expected, given the growth rate, as narrow spacing experiences slow radial growth and is associated with higher wood density. Additionally, the influence of growth rate could likely be attributed to the difference in latewood and earlywood proportions between slow- and fast-growing planted trees.

Few studies have been conducted on the spacing effects on the wood properties of *T. grandis* at young ages in different tropical countries. In Indonesia, the study by Rahmawati et al. (2022) reported no significant effect of spacing on the physical and mechanical properties of 8-year-old *T. grandis*. Furthermore, they exhibited a decreasing trend in mechanical properties with increasing spacing. In Tanzania, studies only assessed 14-year-old trees, while the present study addresses 24-year-old trees. Zahabu et al. (2015) reported no significant difference in the physical and mechanical properties of 14-year-old *T. grandis* at three different spacings. Moreover, at the same age, Sibomana et al. (1997) demonstrated a significant difference in the mean values of the physical and mechanical properties of 14-year-old *T. grandis* trees at four different spacings in Tanzania.

Regarding wood properties, studies have reported a substantial increase in properties such as wood density, modulus of elasticity, and modulus of rupture at older ages. These properties tend to increase due to an increase in cellular wall thickness, while decreasing vessel frequency (Li et al. 2019). Wood properties such as wood density, heartwood percentage, modulus of elasticity, modulus of rupture, compressive strength parallel to the grain, shear strength parallel to the grain, and cleavage strength, have not been studied in older-aged trees, and no published data exist for *T. grandis* aged 24 years under different spacings in Tanzania. This study assessed the effects of spacing on the physical and mechanical properties of *T. grandis* at an older age of 24 years. The results guide tree growers on the effects of spacing at older ages, specifically on wood quality in terms of physical and mechanical properties.

2. Materials and Methods

2.1. Study Area Description

The spacing trial is located at Longuza Forest Plantation in Muheza District, Tanga Region. It lies at an altitude of 180 m above sea level between 4° 48' and 5° 13' S latitudes and 38° 32' and 38° 48' E longitudes. The rainfall occurs biannually, with an average annual rainfall of 1,548 mm. The long rains occur from March to May, followed by the short rains from October to December.

The dry season occurs from June to September. The area experiences a maximum temperature range of 26°C to 32°C, while the minimum temperature ranges from 15°C to 20°C. The topography is characterized by undulating lower slopes with angles ranging from 5.71° to 11.31° and a steeper upper slope with angles ranging from 14.04° to 19.29°. The soil texture is sandy clay loam, characterized by a dark reddish-brown to dark red colour that becomes redder with depth, and a pH range of strongly acidic (4.5–5.0) to neutral (6.6–7.3). The soil in the area varies from relatively shallow (less than 20 cm deep) to exceptionally deep (exceeding 120 cm), with the majority falling within the moderately deep category (ranging from 40 to 80 cm in depth) (Zahabu et al. 2015).

2.2. Experimental Design

The study was conducted in a 24-year-old teak (*Tectona grandis*) spacing trial with a complete randomised block design. The trial consisted of three treatments: 2 m × 2 m, 3 m × 3 m, and 4 m × 4 m, each replicated three times. Each plot is planted with 25 seedlings from the same genetic source in a 5 m × 5 m tree layout with two guard rows of trees to avoid edge effects.

2.3. Sampling and Specimen Preparation

Data collection was conducted in December 2022, where three trees (one per replicate) with straight stems, normal branching, free from disease or pest attack, and without any physical defects were randomly selected at each spacing, felled, and marked accordingly, totaling nine randomly sampled trees. Disks 5 cm thick were cut at breast height (1.3 m), 30%, 60%, and 90% of the total tree height. A billet of 1 m length was cut at breast height upward (1.3 m), 30%, 60%, and 90% of the total tree height and marked for mechanical properties evaluation. The billets were sawn to a cant measuring 65 mm thick and 1 m long with a pith in the centre. The cants were resawn into planks from the pith, left and right, towards the bark. The planks were numbered and labeled accordingly to indicate their extraction position, and then air-dried in the laboratory to a moisture content of about 12%.

The physical properties determined were wood density (D) and heartwood percentage (HWP). The radius of each disk, from the pith to the HW-sapwood boundary and under the bark, was measured using a vernier caliper in four directions, along the longest axis and perpendicular to it. The HWP was visually determined using the cross-sectional area of the HW and the underbark of the disk (Kokutse et al. 2010; Yang et al. 2020). Then, two opposite wedges extending from the pith to the bark were cut from each disk for density. From each wedge, four samples were cut at 1%, 33%, 66%, and 100% of the total wedge length (Barros-Junior et al. 2022). Wood density was determined by using oven-dry weight and green volume. The green volume was determined by using the water displacement method. For oven-dry weight, samples were dried at 100°C until a constant weight was achieved, and then cooled in desiccators. Additionally, disks for wood density were placed in a plastic bag immediately after cutting and then transported to the laboratory for processing into wood density samples.

The mechanical properties tested were the modulus of elasticity (MOE), modulus of rupture (MOR), compressive strength parallel to the grain (CSP), shear strength parallel to the grain (SS), and cleavage strength (CLS). Test specimens for mechanical properties were prepared from air-dried planks, following the method described by Lavers (1969). The size of the test specimen for MOE and MOR was 20 mm × 20 mm × 300 mm. For CSP, SS, and CLS, the dimensions were 20 mm × 20 mm × 60 mm, 20 mm × 20 mm × 20 mm, and 20 mm × 20 mm × 45 mm, respectively.

Then, mechanical properties were tested according to BS 373 (1957), Ishengoma and Nagoda (1991), and Lavers (1969) using a Monsanto tensiometer machine, and deflection curves were plotted manually. Hereafter, during testing, the test specimens with a moisture content below or above 12% were corrected to 12% using the formula by Desch and Dinwoodie (1981). The moisture content of the test specimens was determined by subtracting the oven-dry weight from the weight of the test specimens.

2.4. Data Analysis

2.4.1. Physical properties

Wood density (D) and heartwood percentage (HWP) were calculated using Equations 1 and 2.

$$D\ (g/cm^3) = \frac{W_{od}}{V_g} \tag{1}$$

where W_{od} and V_g are oven-dry weight (g) and volume (cm^3) of the wood sample.

$$HWP\ (\%) = \frac{H_{CA}}{D_{CA}} \times 100\% \tag{2}$$

where H_{CA} is heartwood cross-sectional area, D_{CA} is disk under bark cross-sectional area (including heartwood and sapwood).

2.4.2. Mechanical properties

The MOE and MOR were tested using the central loading method with a span length of 280 mm. The analysis for all mechanical properties was computed from three height levels: DBH, 30% of the total height, and 60% of the total height, as the 90% height level did not have clear specimens for testing. MOE, MOR, CSP, SS, and CLS were determined using Equations 3–7.

$$MOE\ (N/mm^2) = \frac{P\,L^3}{4Ybd^3} \tag{3}$$

$$MOR\ (N/mm^2) = \frac{3PL}{2bd^2} \tag{4}$$

where *MOE* is modulus of elasticity, *MOR* is modulus of rupture, *P* is maximum load in Newton's (N), *L* is span length (mm); *b* is width of the test sample (mm), *P* is load in Newton's to limit of proportionality, *d* is depth of the test sample (mm), and *Y* is deflection in mm at midlength at limit of proportionality.

$$CSP\ (N/mm^2) = \frac{P\ (max)}{A} \tag{5}$$

where *CSP* is compressive strength (N/mm^2), *P (max)* is maximum crushing load in Newton's (N), and *A* is cross-sectional area (mm^2).

$$SS\ (N/mm^2) = \frac{P}{A} \tag{6}$$

where *SS* is shear strength parallel to the grain, *P* is the maximum load (N), and *A* is the area in shear (mm^2).

$$CLS (N/mm) = \frac{P\ (max)}{A} \tag{7}$$

where *CLS* is cleavage strength, *P* is maximum load (N), and *B* is specimen width (mm).

2.5. Statistical Analysis

The effect of spacing on all studied physical and mechanical properties was evaluated using one-way analysis of variance (ANOVA), with the Tukey honest significant difference test employed for multiple comparisons among the spacings. The statistical analysis was performed using the R system for statistical computing (R Core Team 2016).

3. Results and Discussion

3.1. Effects of Spacing on Physical Properties

The spacing effects on wood density and HWP of *T. grandis* at 24 years old are presented in **Tables 1** and **2**, respectively. Spacing had no significant effect on wood density at all height levels. The higher wood density was observed at a spacing of 2 m × 2 m compared to the other spacings of 3 m × 3 m and 4 m × 4 m. Additionally, in all three spacings, wood density exhibited an increasing trend with height, except at 30% height levels, where a slight decrease was observed. On the other hand, HWP did not differ significantly at any height level, except at DBH, where the 2 m × 2 m spacing differed significantly from the 4 m × 4 m spacing. The 4 m × 4 m spacing produced higher HWP at the DBH and 30% height levels compared to the other two spacings. However, at 60% and 90% height levels, the 2 m × 2 m spacing produced the highest HWP. The overall trend of HWP is not directional, as HWP decreased from 2 m × 2 m to 3 m × 3 m, then increased to 4 m × 4 m.

Table 1. Effect of spacing on the density of *Tectona grandis*

Spacing	Density (g/cm^3)				
	DBH	30%	60%	90%	Overall mean
2 m × 2 m	0.53 ± 0.04^a	0.51 ± 0.06^a	0.59 ± 0.05^a	0.63 ± 0.05^a	0.57 ± 0.07^a
3 m × 3 m	0.50 ± 0.07^a	0.48 ± 0.02^a	0.55 ± 0.07^a	0.59 ± 0.07^a	0.53 ± 0.07^a
4 m × 4 m	0.52 ± 0.05^a	0.48 ± 0.02^a	0.54 ± 0.06^a	0.59 ± 0.07^a	0.53 ± 0.06^a
F value	0.22	0.70	0.57	0.45	1.15

Notes: Across the column, the same letter implies that the means are not statistically different among the spacings ($p > 0.05$).

Table 2. Effect of spacing on heartwood percentage of *Tectona grandis*

Spacing	HWP (%)				
	DBH	30%	60%	90%	Overall mean
2 m × 2 m	64.81 ± 1.70^b	64.38 ± 0.76^a	51.05 ± 7.12^a	22.24 ± 2.84^a	50.62 ± 18.37^a
3 m × 3 m	66.78 ± 4.73^{ab}	64.06 ± 4.82^a	49.08 ± 4.11^a	18.01 ± 9.12^a	49.48 ± 20.89^a
4 m × 4 m	74.42 ± 2.68^a	68.51 ± 1.03^a	48.54 ± 3.21^a	17.83 ± 8.61^a	52.33 ± 23.45^a
F value	7.15	2.23	0.20	0.34	0.06

Notes: HW is heartwood percentage. Across the column, the same letter implies means are not statistically different among the spacings ($p > 0.05$), while different letters imply that means are statistically different ($p < 0.05$).

Results revealed a non-significant decreasing trend in wood density with an increase in spacing, even though the 3 m × 3 m spacing had a relatively low wood density compared to the 4 m × 4 m spacing. This may be explained by the fact that an increase in spacing leads to an increase in radial growth. This, in turn, causes an increase in the proportion of earlywood, which is associated with large cell lumens and relatively thin cell walls (Hébert et al. 2016). A similar trend was reported by Zahabu et al. (2015), who observed higher wood density at 2 m × 2 m spacing in 14-year-old *T. grandis*. On the other hand, the HWP showed an increasing trend with increasing spacing, even though the 3 m × 3 m spacing still had a slightly lower HWP compared to the 2 m × 2 m spacing at 24 years old. Similarly, at 14 years old, Zahabu et al. (2015) reported an increase in HWP with increased spacing, where a spacing of 4 m × 4 m had the highest HWP. Furthermore, Rahmawati et al. (2022) observed an increasing trend in HWP with spacing in 8-year-old *T. grandis*.

3.2. Effect of Spacing on Mechanical Properties

The effect of spacing on MOE, MOR, CSP, SS, CLSP, and CLST is presented in **Tables 3–8**, respectively. Spacing had no significant effect on all mechanical properties studied, except for SS and CLST. The SS differed significantly in overall mean values, with the spacing of 3 m × 3 m statistically differing from that of 4 m × 4 m. On the other hand, the CLST differed significantly at DBH, where the spacing of 3 m × 3 m differed statistically from the other two spacings of 2 m × 2 m and 4 m × 4 m. Based on the height levels, all mechanical properties studied at DBH except SS were higher at a spacing of 2 m × 2 m. By contrast, at a 30% height level, the spacing of 2 m × 2 m produced trees with higher values only for MOE, CSP and CLSP, while the higher values for SS and CLST were at the spacing of 3 m × 3 m. Furthermore, at a 60% height level, the spacing of 3 m × 3 m produced trees with higher values for all mechanical properties except for CLST. Generally, the overall mean values of mechanical properties were higher at a 2 m × 2 m spacing, except for SS, and the lower values were observed at a 4 m × 4 m spacing.

Table 3. Effect of spacing on MOE of *Tectona grandis*

Spacing	MOE (N/mm^2)			
	DBH	**30%**	**60%**	**Overall mean**
2 m × 2 m	8,536 ± 910[a]	8,488 ± 483[a]	8,738 ± 741[a]	8,588 ± 713[a]
3 m × 3 m	7,568 ± 1,028[a]	8,301 ± 476[a]	9,521 ± 958[a]	8,464 ± 1,506[a]
4 m × 4 m	6,835 ± 674[a]	8,415 ± 1,147[a]	8,776 ± 1,943[a]	8,009 ± 1,052[a]
F value	2.80	0.05	0.34	0.65

Notes: MOE is the modulus of elasticity. Across the column, the same letter implies that means are not statistically different (p > 0.5), while different letters imply that means are statistically different (p < 0.5).

Table 4. Effect of spacing on MOR of *Tectona grandis*

Spacing	MOR (N/mm^2)			
	DBH	**30%**	**60%**	**Overall mean**
2 m × 2 m	91.16 ± 5.05[a]	84.77 ± 4.70[a]	96.42 ± 10.10[a]	90.78 ± 7.93[a]
3 m × 3 m	82.83 ± 10.44[a]	84.15 ± 13.70[a]	103.14 ± 24.89[a]	90.04 ± 18.05[a]
4 m × 4 m	81.69 ± 7.85[a]	89.38 ± 9.52[a]	96.66 ± 6.37[a]	89.24 ± 9.50[a]
F value	1.23	0.24	0.17	0.03

Notes: MOR is the modulus of rupture. Across the column, the same letter implies that means are not statistically different (p > 0.5), while different letters imply that means are statistically different (p < 0.5).

Table 5. Effect of spacing on CSP of *Tectona grandis*

Spacing	CSP (N/mm^2)			
	DBH	**30%**	**60%**	**Overall mean**
2 m × 2 m	48.98 ± 4.15[a]	49.55 ± 6.59[a]	49.69 ± 5.06[a]	49.41 ± 4.66[a]
3 m × 3 m	42.98 ± 5.20[a]	45.41 ± 7.27[a]	56.00 ± 15.61[a]	48.13 ± 10.81[a]
4 m × 4 m	41.50 ± 3.85[a]	47.18 ± 1.35[a]	52.16 ± 6.34[a]	46.94 ± 5.96[a]
F value	2.39	0.40	0.29	0.24

Notes: CSP is compressive strength parallel to the grain. Across the column, the same letter implies that means are not statistically different (p > 0.5), while different letters imply that means are statistically different (p < 0.5).

The results showed a similar trend of a non-significant decrease with an increase in spacing in all studied mechanical properties, except for SS, where there was a slight increase from 2 m × 2 m to 3 m × 3 m, followed by a decrease to 4 m × 4 m. The same trend was reported by Rahmawati et al. (2022) in 8-year-old *T. grandis*. They reported a non-significant decrease in the MOE, MOR, and CSP with an increase in spacing at four different spacings. Also, at 14 years, Zahabu et al. (2015) reported that mechanical properties decreased non-significantly with an increase in spacing. These included only the MOE, CSP to the grain, SS, and CLSR, while the MOR increased non significantly with spacing. Furthermore, Zahabu et al. (2015) demonstrated that CLST increased significantly with increased spacing. On the contrary, Sibomana et al. (1997) reported that the MOE, CSP, and SS increased significantly at 14 years. Additionally, they reported the MOR increased non-significantly with an increase in spacing at spacings of 2 m × 2 m, 2.5 m × 2.5 m, and 3 m × 3 m.

Table 6. Effect of spacing on the SS of *Tectona grandis*

Spacing	SS (N/mm^2)			
	DBH	**30%**	**60%**	**Overall mean**
2 m × 2 m	9.47 ± 0.73^a	9.55 ± 0.96^a	9.18 ± 0.53^a	9.40 ± 0.68^{ab}
3 m × 3 m	9.85 ± 0.50^a	9.76 ± 0.74^a	9.77 ± 0.50^a	9.79 ± 0.51^a
4 m × 4 m	8.92 ± 0.69^a	9.09 ± 0.49^a	8.92 ± 1.20^a	8.97 ± 0.74^b
F value	1.56	0.62	0.88	3.56

Notes: SS is shear strength parallel to the grain. Across the column, the same letter implies that means are not statistically different ($p > 0.5$), while different letters imply that means are statistically different ($p < 0.5$).

Table 7. Effect of spacing on CLSP of *Tectona grandis*

Spacing	CLSP (N/mm)			
	DBH	**30%**	**60%**	**Overall mean**
2 m × 2 m	14.93 ± 0.90^a	13.79 ± 1.35^a	15.78 ± 1.28^a	14.83 ± 1.35^a
3 m × 3 m	13.10 ± 0.56^a	13.43 ± 1.54^a	14.65 ± 3.20^a	13.72 ± 1.93^a
4 m × 4 m	13.12 ± 1.79^a	12.82 ± 0.62^a	13.37 ± 1.45^a	13.10 ± 1.22^a
F value	2.29	0.48	0.94	2.96

Notes: CLSP is the cleavage strength perpendicular to the grain. Across the column, the same letter implies that means are not statistically different ($p > 0.5$), while different letters imply that means are statistically different ($p < 0.5$).

Table 8. Effect of spacing on CLST of *Tectona grandis*

Spacing	CLST (N/mm)			
	DBH	**30%**	**60%**	**Overall mean**
2 m × 2 m	16.98 ± 0.29^a	15.50 ± 1.88^a	17.65 ± 1.16^a	16.71 ± 1.47^a
3 m × 3 m	15.30 ± 0.66^b	15.53 ± 2.83^a	17.94 ± 2.13^a	16.26 ± 2.20^a
4 m × 4 m	16.60 ± 0.24^a	14.00 ± 1.09^a	15.34 ± 2.68^a	15.32 ± 1.84^a
F value	11.91	0.54	1.40	1.32

Notes: CLST is cleavage strength tangential to the grain. Across the column, the same letter implies that means are not statistically different ($p > 0.5$), while different letters imply that means are statistically different ($p < 0.5$).

4. Conclusions

Results from the *Tectona grandis* spacing trial showed that only SS showed significant differences at the age of 24 years. However, spacing did not statistically affect all studied physical and mechanical properties; results showed a non statistically decreasing trend in all physical and mechanical properties with an increase in spacing, except for HWP and SS. The highest overall mean values of density, MOE, MOR, CSP, CLSP and CLST were observed at a closer spacing of 2 m × 2 m. Furthermore, the lowest mean values of these properties were observed at a wider spacing of 4 m × 4 m, except for wood density and HWP, which were observed at a spacing of 3 m × 3 m. On the other hand, the highest SS was observed at a spacing of 3 m × 3 m, while the lowest was still at a 4 m × 4 m spacing. Even though there was no significant difference in physical and mechanical properties among spacings, the wood at a spacing of 2 m × 2 m tended to show higher values of its physical and mechanical properties; the properties did not differ much with a spacing of 3 m × 3 m, and the wood at a spacing of 4 m × 4 m showed a greater decrease in properties compared to 2 m × 2 m. Generally, it is recommended that when considering the quality of *T. grandis*, a spacing of 2 m × 2 m is most appropriate, as it tends to have higher average values in most properties in terms of physical and mechanical properties.

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Author Contributions

E.S.: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation; J.N.M.: Writing – Review and Editing, Visualization, Supervision; S.A.O.C: Writing – Review and Editing, Visualization, Supervision.

Conflict of Interest

The authors declare no conflict of interest.

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

Not applicable.

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