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Technological Characterization of Teak Wood from Plantation Thinnings in the Southeastern Peruvian Amazon

Roger CHAMBI-LEGOAS[1,†] · Nataly Estefani CARPIO-MENDOZA[1] · Bianca Ruth COLLAZOS-MENDOZA[2] · Leif Armando PORTAL-CAHUANA[3]

ABSTRACT

Tectona grandis (teak) is a highly valuable forest species in the timber industry due to the quality and durability of its wood. Thinnings in teak plantations generate a significant volume of wood that is not utilized for timber products due to the lack of knowledge about the wood characteristics of these trees. This study evaluated the anatomical, physical, and mechanical properties of 6-year-old *T. grandis* wood from thinning operations in a commercial plantation in the Madre de Dios region of Peru, in order to determine its viability for the production of timber products. The main objective was to assess whether this juvenile wood, despite its early age, is suitable for various industrial applications. Anatomical, physical, and mechanical analyses were performed on samples taken from nine trees. The results indicated that the wood has a well-defined anatomical structure, with an average basic density of 0.49 g/cm^3 and moderate volumetric shrinkage. Regarding mechanical properties, the wood showed adequate stiffness (Modulus of Elasticity, MOE: 87,410.99 kg/cm^2), though with limited resistance to compression parallel to the grain. The results suggest that, despite certain limitations in properties such as compression resistance, 6-year-old thinning wood of *T. grandis* has considerable potential for applications in furniture, carpentry, and non-structural construction. In conclusion, 6-year-old teak wood demonstrates sufficiently good physical and mechanical properties for use in medium-demand industrial applications. This finding opens the door to future research that expands the use of thinning wood in a wider range of products, ensuring sustainable use of plantations in the region.

Keywords: industrial applications, wood quality, forest thinning, sustainability, *Tectona grandis*

1. INTRODUCTION

Tectona grandis L.f., known as teak, is a species native to Southeast Asia that has spread widely across tropical regions due to the high quality of its wood. This species has been planted in over 60 countries, valued for its high resistance and durability, making it one of the most prized woods worldwide. In Latin America, particularly in Peru, teak plantations are concentrated in regions such as Huánuco and Madre de Dios, where the

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[1] Department of Forestry and Environmental Engineering, National Amazonian University of Madre de Dios, Puerto Maldonado 17001, Perú
[2] Misni SAC Reforesting Company, Tahuamanu 17200, Perú
[3] Institute for Research in Forestry and Tropical Ecosystems - INIFET, Professional School of Forestry Engineering, Faculty of Agricultural Engineering and Sciences, Toribio Rodríguez de Mendoza National University of Amazonas, Chachapoyas 01001, Perú
[†] Corresponding author: Roger CHAMBI-LEGOAS (e-mail: rchambi@unamad.edu.pe, https://orcid.org/0000-0001-8473-0462)

first teak plantations were established in 2010 using selected seeds and high-productivity clones from Brazil and Costa Rica. Teak plantations in Latin America follow a rotation cycle of approximately 20 years, which not only guarantees a good volume of wood but also trunks with large diameters and minimal defects. These short-rotation periods have proven effective in obtaining high-quality wood, with properties that have been widely studied in trees aged 13 to 22 years, with the particularity that the wood of young teak plantations exhibits quality comparable to that of long-rotation plantations (Jerez-Rico and de Andrade Coutinho, 2017).

The anatomy of *T. grandis* wood is fundamental to understanding its properties. This species is characterized by well-defined growth rings, distinguishable both macroscopically and microscopically. The wood features semi-annual porosity, with vessels distributed in the latewood zone and marginal parenchyma, giving it a clear and coherent structure (Dominguez-Salcedo and Portal-Cahuana, 2024; Quintilhan *et al*., 2021). Additionally, the size and frequency of the vessels, which vary with the tree's age, affect the circulation of water and nutrients, directly impacting the wood’s mechanical properties and durability (Chuquicaja Segura *et al*., 2020). In young woods, fibers are thinner-walled and shorter in length compared to older woods, influencing the wood’s strength and flexibility characteristics (Cardoso *et al*., 2015).

The physical and mechanical properties of teak wood are crucial for determining its suitability for different applications. The density of the wood is a key parameter, as it is related to durability, ease of processing and resistance to deformation. Teak wood, in particular, has a moderate density, making it suitable for a variety of uses, from furniture to construction structures. Furthermore, teak demonstrates good dimensional stability (Moya and Muñoz, 2010), meaning it has low volumetric shrinkage, an important feature for applications in environments with fluctuating humidity (Telles Antonio *et al*., 2017). Mechanical properties such as modulus of elasticity (MOE) and bending strength are also notable, making teak wood a viable option for structural uses requiring high stiffness and load-bearing capacity. However, it has been observed that the resistance to compression parallel to the grain in young wood is relatively low, which may limit its use in applications that require high compression resistance (Rivero-Moreno and Moya-Roque, 2006). Teak wood has high quality, medium density, moderate strength, and high durability (Miranda *et al*., 2011; Seta *et al*., 2023; Wanneng *et al*., 2014).

Despite advances in the study of short-rotation teak plantations, there is a lack of information on the quality of wood from the first thinnings, which typically involves trees between 3 to 6 years old. In this context, the question of the feasibility of using thinning wood from teak for the production of timber products becomes crucial. Often, thinning wood is considered lower quality or non-commercial (Bhat *et al*., 2001; Seta *et al*., 2023), although some studies have suggested that the quality of young wood may be suitable for certain industrial products if properly utilized (Rios *et al*., 2021; Rivero-Moreno and Moya-Roque, 2006). Particleboard from teak sawdust is a sustainable alternative to traditional wood with the aim of reducing waste (Chauhan *et al*., 2021; Hermawan *et al*., 2024; Ikubanni *et al*., 2018; Wanishdilokratn and Wanishdilokratn, 2024).

The main objective of this study was to evaluate the anatomical characteristics, physical properties, and mechanical properties of 6-year-old *T. grandis* wood, removed during the first thinning operation of plantations in southeastern Peru. The research focused on determining the feasibility of using this wood in timber products to contribute to the sustainable use of forest resources in the region. The following research questions were posed: What are the anatomical, physical, and mechanical characteristics of 6-year-old *T. grandis* wood removed during the first thinning? Is it viable to use teak thinning wood for the production of timber products? This study aimed to provide a deeper understanding of teak thinning wood, contributing to the sustainable development of plantations and expanding knowledge about its feasibility for industrial products.

2. MATERIALS and METHODS

2.1. Study area

This study was conducted in the Madre de Dios region, located in the southeastern Amazon of Peru, which is part of the Critical Biodiversity Hotspots for Conservation Priorities (Myers *et al*., 2000), underscoring its global relevance in terms of conservation. Madre de Dios harbors a remarkable diversity of ecosystems, including tropical rainforests that serve as a vital habitat for a wide range of flora and fauna species. Among the most representative plant species in the region are *Bertholletia excelsa*, *Cedrela odorata*, and *Swietenia macrophylla* (Lopes *et al*., 2023), which are characteristic of the tropical rainforest that dominates the area.

The study area is located in a commercial plantation of *T. grandis* (teak), situated at kilometer 645 of the interoceanic highway Puerto Maldonado - Iñapari, covering an area of 424 hectares. The plantation's elevation ranges from 200 to 210 meters above sea level. This location lies in a transition zone between the Amazon and Andes ecosystems, contributing to its ecological uniqueness (Fig. 1).

The region's soils belong to the Iñapari Series,

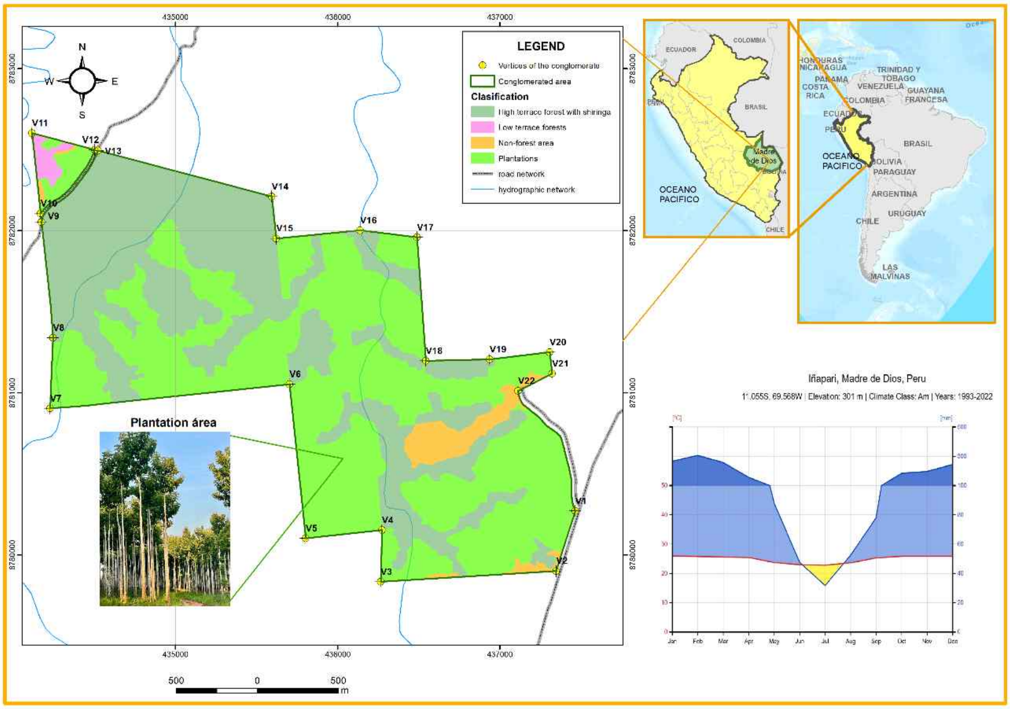

Fig. 1. Study area map. A climatic diagram for the period 1993–2022 (Zepner *et al*., 2021) is shown, where the red line represents the average temperature, the blue area represents the rainy season, the dark blue area represents precipitation exceeding 100 mm, and the yellow area represents the dry season. Additionally, a photo of the plantation is included.

classified as Ultic Hapludalfs, which are characterized by being deep, well-drained, and permeable, with a medium to moderately fine texture. These soils have a moderately acidic pH (ranging from 5.2 to 5.8) and low natural fertility, with limited organic matter and phosphorus content, but are rich in potassium (IIAP and WWF, 2006).

The climate of the area is tropical humid, with an average annual precipitation of 159 mm and an average annual temperature of 24.9℃ (Zepner *et al*., 2021). The region experiences two well-defined seasons: the dry season, which lasts from May to October, and the rainy season, which runs from November to April (Portal-Cahuana *et al*., 2023).

2.2. Wood sampling and preparation

Wood samples were obtained from nine 6-year-old thinning trees of *T. grandis*, randomly selected from a commercial teak plantation owned by Reforestadora Misni SAC, which spans an area of 424 hectares. The selection of this species is based on its potential economic relevance in the region, being one of the most widespread forest crops in Madre de Dios, specifically in the province of Tahuamanu. Furthermore, its use in the local and international timber industry justifies its inclusion in this study, which aims to technologically characterize the wood of *T. grandis* from thinning plantations, with the goal of evaluating its potential in various industrial processes.

From each tree, a cross-sectional disc was extracted at breast height, with a length of 1 meter. The size of the sampled trees was representative of the plantation (Table 1).

From these discs, specimens were cut to the specific dimensions required for each type of test, as shown in Table 2.

The selection and preparation of the specimens were carried out following the guidelines established by the Technical Standard NTP N°251.008 (INACAL, 2016a): "Selection and Collection of Samples," ensuring the validity and reliability of the results obtained in the various analyses. In this way, the appropriate conditions were ensured for evaluating the anatomical, physical, and mechanical properties of *T. grandis* wood from thinning plantations in the Madre de Dios region.

Table 1. Dendrometric characteristics of 6-year-old *Tectona grandis* thinning trees for physical, mechanical, and anatomical tests in the Tahuamanu forests, Madre de Dios, Peru

Tree	Dbh (cm)	Bole height (m)
1	16.2	11.7
2	15.7	12.9
3	18.4	13.7
4	19.3	14.1
5	17.7	14.6
6	20.5	17.0
7	18.8	11.8
8	18.5	14.9
9	19.3	14.6
Average	18.3	13.9

Dbh: diameter at breast height.

2.3. Anatomical characterization of wood

The anatomical analysis was conducted out at the Wood Anatomy Laboratory of the National Amazonian University of Madre de Dios (UNAMAD), following the protocol established by the International Association of Wood Anatomists (IAWA, 1989).

2.4. Obtaining histological sections

Nine 1 × 1 cm cubes were prepared for histological sections (9 transverse, 9 tangential, and 9 radial). The microtome blade was adjusted in the appropriate direc-

Table 2. Dimensions and number of specimens for anatomical, physical, and mechanical tests

Test	Dimensions in cm (thickness × width × length)	Number of specimens per tree	Number of 6-year-old trees	Technical standard
Anatomical characterization	1 × 1 × 1	1	9	IAWA (1989)
Physical properties				
Moisture content	3 × 3 × 10			INACAL (2016b)
Basic density	3 × 3 × 10	1	9	INACAL (2016c)
Volumetric shrinkage	3 × 3 × 10			INACAL (2016d)
Mechanical properties				
Compression parallel to the grain	5 × 5 × 20	6	9	ASTM (2023b)
Static bending	5 × 5 × 75	6	9	ASTM (2023a)
Hardness	5 × 5 × 15	4	9	ASTM (2023b)
Shear	5 × 5 × 6.3	4	9	ASTM (2023b)

IAWA: International Association of Wood Anatomists, INACAL: Instituto Nacional de Calidad, Peru, ASTM: American Society for Testing and Materials.

tion and height, and the samples, previously moistened with a solution of glycerin and water, were placed in the Leica horizontal sliding microtome model SM2010R, set to a thickness of 8–14 microns to obtain fine and complete cuts (Marcelo-Peña *et al*., 2019). The sections obtained were transferred to microscope slides with the help of a brush, carefully smoothing them in case they rolled up. They were then covered with aluminum foil to prevent degradation and prepared for microscopic observation at 4 × and 10 × magnification, verifying the quality of the sections under the microscope.

2.5. Obtaining and mounting semi-permanent histological slides

The histological slides underwent a meticulous cleaning process with a bleach solution for five minutes, followed by a wash with distilled water using a dropper to remove any bleach residue. For staining, safranin was applied with a syringe, covering each sample completely, allowing the various wood tissues to be clearly distinguished. After resting for 3 to 5 minutes (depending on the hardness of the material), the samples were gradually washed with distilled water, ensuring that the washing liquid was clear before each change of solution. For long-term conservation (over three months), the best dehydrated histological slides were selected and placed on clean slides, maintaining proper orientation (transverse, radial, and tangential cuts) and free of residues. A drop of glycerin was then added to each sample, a cover slip was placed at an angle, and pressed with a metal rod to prevent bubble formation. Finally, the edges were sealed with nail polish to ensure their preservation.

2.6. Obtaining semi-permanent macerated slides

Radial shavings of 1 cm^3 were cut from each sample cube and placed in test tubes. To each tube, 8 mL of 30% hydrogen peroxide and 8 mL of glacial acetic acid were added, maintaining an equal proportion of both reagents. The tubes were incubated in an oven at 72℃

for 48 hours, allowing the shavings to soften and acquire a white or translucent coloration. Afterward, the shavings were extracted with tweezers and placed in a Petri dish, where they were stained with a drop of diluted safranin for uniform coloration and to facilitate the differentiation of the tissues. After adding a drop of glycerin, a needle was used to flatten the samples and separate the fibers. Once the fibers were adequately separated, they were covered with a cover slip, avoiding bubbles, and sealed with nail polish to ensure long-term preservation (Sass, 1951).

2.7. Physical properties testing

The study to determine the physical properties was conducted in the Wood Properties Laboratory of the UNAMAD. The tests and calculations were performed in accordance with the Peruvian Technical Standards for moisture content (MC), density, and shrinkage (INACAL, 2016b, 2016c, 2016d).

The measurements were carried out in two stages:

Wet stage: The specimens were submerged in water for a minimum period of 10 days until full saturation was achieved. In this condition, known as wet or green, the wet weight (Ww) was measured using an analytical balance, and the wet volume (Wv) was determined using a precision balance with an accuracy of 0.1 g. The dimensions of the specimens (width and length) were also recorded using a micrometer and a digital caliper, both with an accuracy of 0.1 mm.

Oven drying stage: The specimens were then placed in an electric oven, where the temperature was gradually increased to 103 ± 2℃, with daily weight measurements taken. The drying process continued until the specimens reached a constant weight. Once dried, the specimens were removed and placed in a desiccator with a drying agent "Silicagel" to cool down. Immediately after cooling, they were weighed to obtain the oven-dry weight and the width and length dimensions were measured in this state.

2.8. Calculations

2.8.1. Moisture content

Based on the Peruvian Technical Standard for Moisture Content (INACAL, 2016b), MC (%) was determined by relating the wet weight (Ww) and dry weight (Dw) [Equation (1)].

$$MC\ (\%) = \frac{Ww - Dw}{Dw} \times 100 \qquad (1)$$

Where = Ww: wet weight (g), Dw: dry weight (g).

2.8.2. Basic density

The calculation of basic density (BD) in g/cm^3 was carried out following the Peruvian Technical Standard for density (INACAL, 2016c) [Equation (2)].

$$BD = \frac{Dw}{Wv} \qquad (2)$$

Where = Dw: dry weight (g), Wv: wet volume (cm^3).

2.8.3. Volumetric shrinkage

To determine the volumetric shrinkage, the Peruvian Technical Standard on shrinkage (INACAL, 2016d) was followed. The data obtained from the measurements of wet and dry dimensional volumes were used by the immersion method, applying the formula in Equation (3):

$$\text{volumetric shrinkage}\ (\%) = \frac{Wvd - Odvd}{Odvd} \times 100 \qquad (3)$$

Where = Wvd: wet volumetric dimension (cm^3), Odvd: oven-dried volumetric dimension (cm^3).

2.9. Mechanical properties testing

The 9 specimens used to evaluate the mechanical properties, one from each tree corresponding to the 6-year-old samples, were prepared from specimens with MC at equilibrium. The tests were conducted at the Wood Anatomy Laboratory of the National Agrarian University of La Molina in Lima, following the specifications of the international standards from the American Society for Testing and Materials (ASTM, 2023a, 2023b).

2.9.1. Static bending test

This process was carried out according to the standard (ASTM, 2023a), and the calculations were based on the following equations [Equations (4) to (6)]

$$ELP = \frac{3P'L}{2\ ae^2} \tag{4}$$

$$MOR = \frac{3PL}{2\ ae^2} \tag{5}$$

$$MOE = \frac{P'L^3}{4ae^3Y} \tag{6}$$

Where = ELP: fiber stress at the proportional limit in kg/cm^2, MOR: modulus of rupture in kg/cm^2, MOE: modulus of elasticity in kg/cm^2, P’: load at the proportional limit in kg, P: maximum load in kg, L: span of the specimen (distance between supports), measured in cm. Primary method: 5 cm × 5 cm × 76 cm specimens with a span (L) of 70 cm. Secondary method: 2.5 cm × 2.5 cm × 41 cm specimens with a span (L) of 35 cm, a: width of the specimen in cm, e: thickness of the specimen in cm, Y: deflection at the center of the span at the proportional limit in cm.

2.9.2. Parallel-to-grain compression test

Based on ASTM D143-21 (ASTM, 2023b). The compressive strength and MOE were determined using the following equations [Equations (7) to (9)]:

$$ELP = \frac{P'}{A} \tag{7}$$

$$RM = \frac{P}{A} \tag{8}$$

$$MOE = \frac{P'L}{A\ D} \tag{9}$$

Where = ELP: fiber stress at the proportional limit in kg/cm^2, RM: maximum resistance to axial compression in kg/cm^2, MOE: modulus of elasticity in kg/cm^2, P’: load supported by the specimen up to the proportional limit in kg, P: maximum load supported by the specimen in kg, A: cross-sectional area of the specimen calculated before the test, in cm^2, D: deformation experienced by the specimen at the proportional limit, in cm.

2.9.3. Hardness test

This process was carried out according to ASTM D143-21 (ASTM, 2023b). The hardness was evaluated on both the ends and the sides of the specimens. The values were expressed in kg/cm^2. No specific formula was used, as the result is a direct reading from the testing equipment.

2.9.4. Parallel-to-grain shear test

The test followed the ASTM D143-21 standard (ASTM, 2023b). The shear strength was calculated using the following formula [Equation (10)]:

$$CZ = \frac{P}{A} \tag{10}$$

Where = CZ: parallel-to-grain shear, P: maximum load (kg), A: shear area.

2.10. Data processing and analysis

For the data analysis, Excel was used for organizing tables, and R software version 4.4.2 with the Rstudio interface (R Core Team, 2025) was employed to generate correlations graphs between anatomical, physical, and mechanical characteristics.

Anatomical measurements were made using a Leica microscope, with 4 × and 10 × objectives, combined with the software LAS-EZ-3.4-DVD-272 and ImageJ-win64.exe. LAS-EZ-3.4-DVD-272 was used to capture images of all histological features, while ImageJ-win64.exe was used to calculate anatomical dimensions. For the measurements, 35 photographs were taken to measure fiber length (at 4 ×), 25 to analyze the cell wall (at 10 ×), 4 of cross-sections (at 4 ×), 4 of tangential cuts (at 4 ×), and one of the radial surface (at 10x) for each sample. The images were inserted into ImageJ, where the scale was adjusted using the "Set Scale" function to ensure measurement accuracy.

3. RESULTS and DISCUSSION

3.1. Wood anatomy of 6-year-old *Tectona grandis*

The wood of 6-year-old thinned *T. grandis* exhibited growth rings delimited by marginal paratracheal parenchyma and semicircular porosity. Additionally, the vessels had an average tangential diameter of 146.25 ± 69.51 μm, showing notable variability in their size, primarily due to the semicircular porosity. The vessel frequency was 5.37 ± 0.78 vessels/mm^2 (Table 3), indicating a relatively homogeneous distribution of these anatomical elements (Fig. 2).

Regarding the fibers, the average length was 921.34 ± 77.86 μm, while the diameter reached 52.13 ± 4.40 μm, and the cell wall thickness was 8.05 ± 0.51 μm (Table 3). These values reflect a uniform fibrous structure with low variability in their dimensions, suggesting stability in the wood's formation.

The results indicate that 6-year-old *T. grandis* wood presents an anatomical structure characterized by a moderate distribution of vessels and fibers with stable morphology. The high variability observed in the vessel diameter may influence permeability and the efficiency of liquid transport, even considering the presence of gums and tyloses in the vascular lumen. On the other hand, the stability in the fiber dimensions suggests a relatively homogeneous structure at this stage of development, which could favor its performance in future structural and commercial applications.

These characteristics are key for assessing its viability in industrial applications. The juvenile wood shows semi-annual porosity with marginal paratracheal parenchyma, and growth rings that are clearly defined, which

Table 3. Mean values and coefficients of variation for anatomical characteristics of 6-year-old *Tectona grandis* wood from thinning operations in Madre de Dios, Peru

Anatomical variables	Average (6 yr)	Max.	Min.	SD	Coeff. var
Tangential vessel diameter (μm)	146.25	327.65	98.81	69.51	47.53
Vessel frequency (vessels/mm^2)	5.37	6.94	4.29	0.78	14.51
Fiber length (μm)	921.34	1,017.36	732.96	77.86	8.45
Fiber diameter (μm)	52.13	58.92	46.63	4.40	8.43
Fiber wall thickness (μm)	8.05	8.62	6.95	0.51	6.30

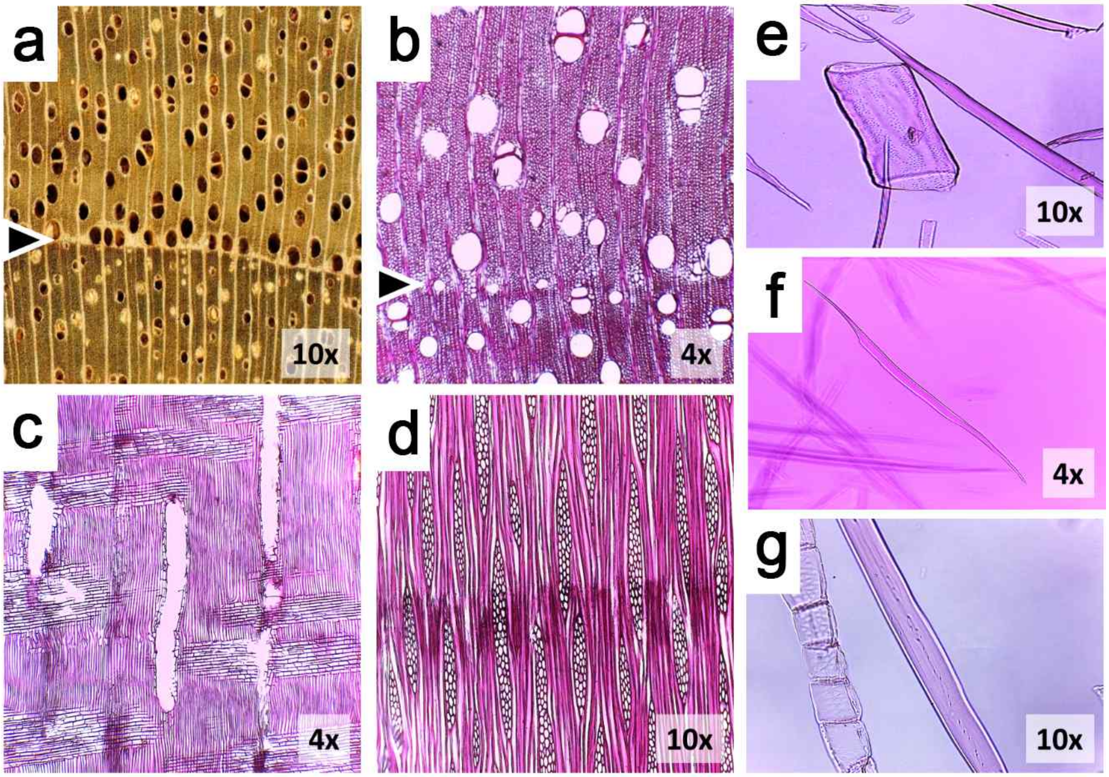

Fig. 2. Macro and microphotographs of 6-year-old *Tectona grandis* wood from thinning operations. (a) Macroscopic cross-section. (b) Microscopic cross-section. (c) Microscopic radial section. (d) Microscopic tangential section. (e) Vascular element. (f) Fiber length. (g) Fiber diameter and wall thickness. The black lines in the cross-section indicate the growth ring boundary.

matches the findings of Quintilhan *et al*. (2021), who also reported that species with this porosity have well-defined rings, making them easier to identify ring boundaries, which not only allow for visual identification of the tree's age but also reflect variations in annual growth, which may influence the wood's technological properties.

The vessel diameter in our juvenile teak is consistent with the findings of Cardoso *et al*. (2015) in woods of different ages, where the vessels of *T. grandis* tend to be smaller in young wood. This value is significantly lower than the diameters reported for adult wood, aligning with trends observed in most studies of juvenile wood from fast-growing species, such as *T. grandis*. The smaller vessel spaces could affect water and nutrient circulation, influencing the mechanical properties and durability of the wood in its early growth stages.

The vessel frequency was moderate compared to the higher frequencies observed in adult wood. According to Chuquicaja Segura *et al*. (2020), vessel frequencies vary depending on the tree's age, being lower in young trees and increasing in older trees. In our study, the frequency of vessels seems adequate for the wood's needs for water and nutrient transport, although this parameter may influence the wood's final quality, especially in terms of permeability and the ability to absorb preservative treatments.

Its moderate fiber length (921.34 μm) and thick wall (8.05 μm) suggest that the wood of these juvenile *T. grandis* has a robust fibrous structure. Chuquicaja Segura *et al*. (2020), in a study conducted with 32-year-old *T. grandis* trees, found a longer fiber of 1,355 μm. While the fibers in this juvenile wood are shorter, they are still within an acceptable range for less demanding structural applications. Souza *et al*. (2019) also reported variability in fiber dimensions depending on site and tree age, highlighting that the wood's mechanical properties are influenced by growing conditions.

3.2. Physical properties of wood

The physical properties of 6-year-old thinned *T. grandis* wood showed characteristic values indicating moderate and stable behavior. The average maximum MC in *T. grandis* wood was 77.70 ± 7.01%, with a range varying between 66.28% and 87.74%. The average BD was 0.49 ± 0.03 g/cm^3, with values ranging from 0.44 g/cm^3 to 0.55 g/cm^3. According to the wood density classification, it is in the "medium" range, which includes values between 0.41 g/cm^3 and 0.60 g/cm^3, indicating a moderate density, suitable for a wide range of industrial applications (Aróstegui *et al*., 1983; Sibille, 2006).

On the other hand, the average volumetric shrinkage was 8.15 ± 1.41%, with a range between 6.45% and 10.66%. According to the classifications, this value falls within the "low" range (7.1% to 10%), suggesting that the wood exhibits relatively low volumetric shrinkage (Aróstegui *et al*., 1983; Sibille, 2006; Table 4).

The maximum MC of 77.70%, is a common characteristic of young wood, which falls within the ranges reported by other studies in *T. grandis*, such as Cunha *et al*. (2020). The variability in MC, ranging from 66.28% to 87.74%, reflects the typical heterogeneity of young trees, which are more susceptible to changes in environmental conditions.

These thinned teak trees were shown to have a medium density wood (0.49 g/cm^3), lower than teak trees from complete rotation (0.59 g/cm^3; Telles Antonio *et al*., 2017), however, that thinned teak wood maintains adequate density for general applications such as furniture and flooring. The medium density also has implications for wood treatment, as its ability to absorb and release moisture affects its dimensional stability and performance in response to environmental changes.

The average volumetric shrinkage of 8.15% is moderate, and suggests that *T. grandis* wood has relatively stable dimensional properties, which is favorable for structural applications and furniture, where deformation due to changes in moisture must be minimal. These findings also compare favorably with the observations of Seta *et al*. (2023), who found that clonal *T. grandis* also exhibits low volumetric shrinkage, making it suitable for environments with fluctuating humidity.

3.3. Mechanical properties of wood

The results for the mechanical properties (Table 5) indicate that, overall, the wood presents adequate rigidity

Table 4. Average values and coefficients of variation for maximum moisture content (MC), basic density, and volumetric shrinkage, of 6-year-old *Tectona grandis* wood from thinning operations in Madre de Dios, Peru

Physical property	Average (6 yr)	Max.	Min.	SD	Coeff. var
MC (%)	77.70	87.74	66.28	7.01	9.01
Basic density (g/cm^3)	0.49	0.55	0.44	0.03	6.63
Volumetric shrinkage (%)	8.15	10.66	6.45	1.41	17.32

Table 5. Average values and coefficient of variation for mechanical properties of 6-year-old *Tectona grandis* wood from thinning operations in Madre de Dios, Peru

Mechanical properties	Average (6 yr)	Max.	Min.	SD	Coeff. var
Static bending					
EFLP (kg/cm^2)	427.26	559.86	350.54	75.94	17.77
MOR (kg/cm^2)	562.19	668.72	482.10	74.00	13.16
MOE (kg/cm^2)	87,410.99	103,326.72	71,890.05	13,737.54	15.72
Parallel to the grain compression					
ELP (kg/cm^2)	240.87	274.34	198.39	34.36	14.26
RM (kg/cm^2)	229.25	299.40	242.04	110.87	48.36
MOE (kg/cm^2)	1,471.60	2,098.70	788.60	526.14	35.75
Hardness					
Hardness at the ends (kg/cm^2)	364.76	392.35	316.75	33.12	9.08
Lateral or side hardness (kg/cm^2)	372.00	436.20	298.99	56.27	15.13
Parallel-to-grain shear (kg/cm^2)	109.94	121.65	95.90	11.71	10.65

EFLP: fiber stress at the proportional limit, MOR: modulus of rupture, MOE: modulus of elasticity, RM: maximum resistance.

to withstand static stresses and moderate resistance to rupture. However, its behavior in parallel-to-grain compression and tangential shear is limited, classifying these parameters as low or medium. Additionally, the wood's hardness falls into the medium category, suggesting intermediate resistance to stresses on lateral and end surfaces. Given that the wood has a moderate BD, its mechanical properties are also characterized by intermediate values, making it suitable for applications where high levels of resistance are not required. These results provide a solid foundation for evaluating the potential of *T. grandis* in various structural and engineering applications, especially in contexts that demand moderate mechanical properties.

Regarding to static bending, the MOE of 87,410.99 kg/cm^2 indicates that 6-year-old *T. grandis* wood exhibits high rigidity, suggesting that it can resist deformation under load without experiencing significant shape changes. However, this value is lower than the reports by Bhat *et al*. (2001), who documented an MOE of 320,000 kg/cm^2 for 7-year-old *T. grandis* trees in India, and by Moya and Muñoz (2010), who found a similar value of 295,420 kg/cm^2 for 6-year-old trees in Costa Rica. Therefore, *T. grandis* wood behaves as a viable option for structural applications where bending resistance is required. On the other hand, the modulus of rupture (MOR) of 562.19 kg/cm^2, which falls into the medium category, reflects a moderate resistance to rupture under bending loads. This behavior is slightly lower than the results obtained by Bhat *et al*. (2001) and Moya and Muñoz (2010), who reported an MOR of 750 kg/cm^2 for *T. grandis* trees in India and Costa Rica, respectively. These values suggest that 6-year-old *T. grandis* wood has sufficient strength to withstand moderate loads but may not be the best option for applications requiring high rupture resistance.

The fiber stress at proportional limit for static bending, with a value of 427.26 kg/cm^2, indicates that wood exhibits intermediate resistance to plastic deformation, which is consistent with findings by Telles Antonio *et al*. (2017) in their study of young *T. grandis* wood. The wood can withstand certain levels of deformation before experiencing permanent alteration. This behavior is particularly relevant for applications involving intermediate stresses or requiring a certain degree of flexibility without losing structural form.

Parallel-to-grain compression, with a value of 240.87 kg/cm^2, falls into the low category, indicating that the wood has limited resistance to compression when fibers are aligned with the load. This value is lower than the 460 kg/cm^2 reported by Rivero-Moreno and Moya-Roque (2006) for 8-year-old trees in Bolivia, though it remains within acceptable ranges for classifying it as a wood with high strength. The differences may be explained by the juvenile nature of the wood in this study and silvicultural management conditions, as reported by Moya and Muñoz (2010), who reported a parallel-to-grain compression resistance value of 350 kg/cm^2 for 6-year-old trees.

Lateral hardness of 372.00 kg/cm^2, classified as medium, reflects moderate resistance to scratching and abrasion. This is consistent with the studies by Telles Antonio *et al*. (2017), who also found similar lateral hardness values for *T. grandis* wood, classifying it as semi-hardwood. This behavior suggests that teak may be suitable for applications where intermediate resistance to wear is required, such as work surfaces or general-use furniture.

Finally, parallel-to-grain shear, with a value of 109.94 kg/cm^2, classified in the low category, indicates that the wood from these thinning *T. grandis* has limited resistance to forces acting tangentially to the fibers. This behavior aligns with the results of Rios *et al*. (2021), who also observed that *T. grandis* wood has low shear resistance, especially in applications where tangential loads are common. These characteristics should be considered when selecting wood for applications involving shear stresses, such as in joints or some structural applications.

3.4. Relationship between wood density and wood anatomy

Anatomical characteristics and wood density was weakly correlated, except for vessel diameter, which showed a significant negative relationship with wood density (r = −0.68; Fig. 3). This implies that trees with larger vessel diameters tend to have lower density, which may affect the physical properties of the wood and its suitability for industrial applications requiring high density and strength. This high relationship may be explained by the fact that *T. grandis* has semicircular porosity (Dominguez-Salcedo and Portal-Cahuana, 2024).

Fiber diameter also showed a significant correlation, with a strong positive relationship to fiber lumen diameter (r = 0.98; Fig. 3). This value suggests that an increase in fiber diameter is associated with an increase

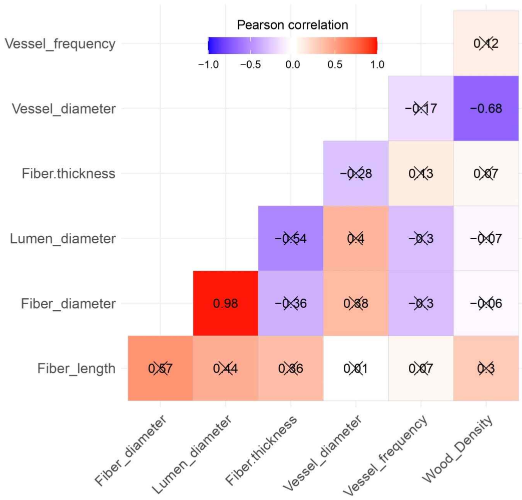

Fig. 3. Pearson correlation matrix between the wood anatomical characteristics and wood density of 6-year-old *Tectona grandis* wood from thinning operations in Madre de Dios, Peru. The “X” indicates the lack of significant correlation.

in lumen diameter, reflecting a consistent microscopic structure in wood formation, as documented in previous studies such as those by Chuquicaja Segura *et al.* (2020), who observed similar relationships in *T. grandis* wood.

Overall, these results indicate that additional biological and environmental factors may play a more significant role affecting wood density (Cardoso *et al.*, 2015; Souza *et al.*, 2019), especially at early growth stages such as those presented in this wood sample.

3.5. Relationship between wood density and mechanical properties

The analysis revealed several strong and significant correlations between key mechanical properties. One of the most notable correlations was observed between the modulus of rupture in static bending (MR_SB) and the fiber stress at the proportional limit in static bending (PLS_SB), with a correlation coefficient of 0.93 (Fig. 4). This result suggests that as the rupture resistance increases, so does the wood's ability to withstand stresses before reaching the proportional limit in static bending.

A significant correlation of 0.86 was also found between PLS_SB and the modulus of elasticity in static bending (ME_SB). This finding indicates that the elasticity of the wood and its bending resistance are closely related, which is essential for understanding the structural behavior of the wood in applications involving bending.

Another important correlation was observed between MR_SB and ME_SB, with a value of 0.95 (Fig. 4), reflecting an extremely strong correlation. This result reinforces the idea that greater elasticity in the wood is linked to a higher capacity to resist rupture under bending loads.

A correlation of 0.96 was found between end hardness and shear strength. This strong correlation suggests that higher compression hardness is associated with greater shear resistance, which has implications for applications requiring resistance in both properties.

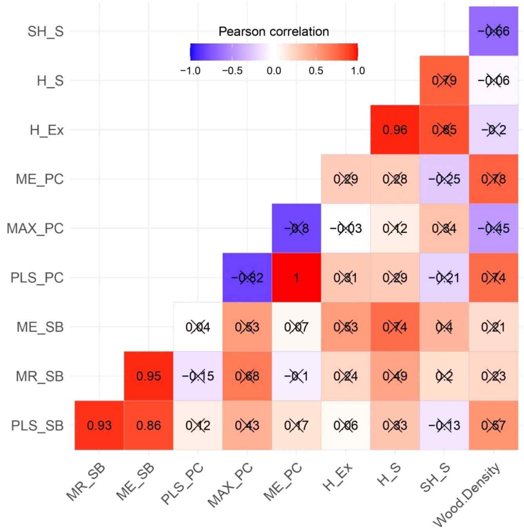

Fig. 4. Pearson correlation matrix between mechanical properties and the density 6-year-old *Tectona grandis* wood from thinning operations in Madre de Dios, Peru. The "X" indicates the lack of significant correlation. SH_S: shear strength (parallel-to-grain shear), H_S: side hardness, H_Ex: end hardness, ME_PC: modulus of elasticity in parallel compression, MAX_PC: maximum resistance in parallel compression, PLS_PC: fiber stress at proportional limit in parallel compression, ME_SB: modulus of elasticity in static bending, MR_SB: modulus of rupture in static bending, PLS_SB: fiber stress at proportional limit in static bending.

Despite the strong correlations in some properties, others did not show statistically significant correlations. The relationships between wood density and various mechanical properties were not significant.

This analysis shows that wood density has a limited impact on the mechanical properties of 6-year-old *T. grandis* wood, highlighting that, although density is a relevant factor for some mechanical properties, it is not the sole determinant, and other variables may be needed to fully understand the behavior of wood in structural and industrial applications. This is consistent with previous studies such as those by Nugroho *et al*. (2024) and Rios *et al*. (2021), which suggest that other structural and biological factors have a more significant impact on mechanical properties than density alone.

The most notable correlation between the MR_SB and the PLS_SB was also observed by Telles Antonio *et al*. (2017), who concluded that higher bending resistance is related to greater elasticity in the wood.

3.6. Potential uses of wood from 6-year-old *Tectona grandis* thinnings

The 6-year-old teak wood from thinnings in Madre de Dios presents properties that could make it suitable for various industrial applications. Its moderate density and dimensional stability suggest that it could be used in furniture and cabinetry manufacturing, such as tables, chairs, indoor shelves, and carpentry work offering possibilities for the production of tool handles and veneer.

It could also be considered for non-structural construction, especially for doors and windows, also moldings and baseboards, due to its low volumetric shrinkage, ease of working, and good appearance. The wood might have potential for use in pallets for the transportation of agricultural products.

4. CONCLUSIONS

This study has characterized the anatomical, physical, and mechanical properties of 6-year-old *T. grandis* wood from commercial plantation thinnings, demonstrating that, despite limitations in certain properties such as parallel compression and shear, the wood could be suitable for various industrial applications, because it shows the necessary rigidity and dimensional stability, making it viable for medium-demand products, thus contributing to the sustainable use of commercial teak plantations in the region. In perspective, the study opens the door for future research on the potential of thinning wood and its viability in a broader range of applications, making this a topic of great interest and relevance in the Peruvian forestry sector.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

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