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ORIGINAL ARTICLE

Isabel Miranda · Vicelina Sousa · Helena Pereira

Wood properties of teak (*Tectona grandis*) from a mature unmanaged stand in East Timor

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Abstract The wood quality from 50- to 70-year-old *Tectona grandis* trees from an unmanaged forest in East Timor was assessed. The aim was to evaluate teak in mature stands that had undergone uncontrolled disturbances, e.g., fire and local community usage. Heartwood represented 91% of the tree radius at a height of 1.7 m, and sapwood contained on average nine rings. The mean ring width showed within-tree and between-tree variability. The chemical compositions of heartwood and sapwood were similar. Within-tree chemical variation occurred only in terms of extractives, which increased from the pith (8.3%) to the heartwood–sapwood transition (12.7%) and decreased in the sapwood (9.2%). Overall, the wood properties of teak from a unmanaged forest in East Timor were comparable to those reported for plantation teaks of other origin: 607 kg/m^3 basic density, 3.5% and 5.2% radial and tangential shrinkage, 141 N/mm^2 modulus of rupture, 10684 N/mm^2 modulus of elasticity, and 50 N/mm^2 maximum crushing strength in compression parallel to the grain. Disturbances on individual tree growth arising from the unmanaged status of the stand were evidenced by higher within-tree variability of ring width. However, the longitudinal and radial variations of wood density and mechanical properties were of low magnitude and in a degree that did not negatively impact on timber quality.

Key words *Tectona grandis* · Chemical composition · Wood properties · East Timor · Unmanaged stands

Introduction

Teak (*Tectona grandis* L.f.) is one of the most valuable and best known tropical timber species and is highly valued for use in shipbuilding, outdoor equipment, furniture, and general carpentry. Teak wood is moderately hard and heavy, seasons rapidly, kiln dries well, and has overall good machining properties. It is prized mostly for its natural durability and high dimensional stability in association with pleasant aesthetics. Some end-user requirements include high heartwood content (at least 85%) and wood density (> 675 kg/m^3) and sufficient strength [modulus of rupture (MOR) > 135 N/mm^2].[1]

Teak grows naturally in Southeast Asia and was introduced into other tropical and subtropical regions in Australia, Africa, and Latin America. Teak is now one of the most important species for tropical plantation forestry, mostly under intensive short rotation management with 20–30 year rotations.[2] Teak is also present in East Timor, an island in Southeast Asia, characterized by tropical and subtropical moist mountain forests totaling 507000 ha that represent 34.3% of the land area.[3] East Timor, an independent country since 2002, is fighting for its economic development, and forests are considered one of the strong drivers, since they include some valuable timber species, particularly teak.

In young plantations, teak wood quality is a matter of research, and some studies have been carried out using teak from different origins, e.g., India,[4] Togo,[5,6] Costa Rica,[7–9] Ivory Coast,[10] and Panama.[11–13] However, teak wood is also provided to a large extent from natural or unmanaged mature forests for which very little information exists in the literature regarding wood quality. This is the case in East Timor, where no data exists on teak wood quality. At present, and due to past political and developmental constraints in East Timor, forests have not been under silvicultural management and have rather evolved under several natural or human-derived disturbances, e.g., fires, illegal logging, and pruning and thinning for local community usage. Additionally, although numerous studies have dealt with teak wood quality, relatively little is known on its chemical composition and within-tree variation.

The present study aims to clarify some of these less researched teak wood properties, namely the chemical composition and the axial and radial variations of properties. A teak plantation established in the period 1940–1950 and then left without forest management and thus subject to fires, felling for local community use, and illegal timber

I. Miranda (✉) · V. Sousa · H. Pereira
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal
Tel. +351-21-369-3378; Fax +351-21-365-3338
e-mail: imiranda@isa.utl.pt

exploitation was used as a case study to exemplify within- and between-tree variation of wood properties in mature trees, i.e., heartwood content, chemical composition, basic density, shrinkage, and mechanical properties.

Material and methods

Sampling

Wood samples were collected from a pure teak stand located in the northeast of East Timor in the Lautem district between Los Palos and Fuiloro (08º30′S, 126º59′E, altitude 380 m). The climate is tropical with distinct wet and dry seasons determined by monsoon influence; data for the Los Palos region is available only for the period 1953–1974 (unpublished data), indicating a 23.8ºC mean annual temperature and 1924 mm mean annual rainfall. August, September, and October are the driest months (mean monthly rainfall less than 32 mm), and July and November are transition months (125 and 94 mm respectively). The site has a declivity of less than 5% and soils of medium texture with pH 7.2.

The stand is a pure teak plantation with an area of approximately 4 ha that was established by the Portuguese regional forest services in the period 1940–1950 with 4 m × 2 m spacing. The seed source is unknown. The stand was unmanaged until sampling, and the present mean tree density is 165 trees/ha. Records on eventual first thinning prior to 1974 (the end of the Portuguese administration) are not available, but field observations clearly showed that the tree density reduction to the present value was the result of unplanned disturbances leading to tree distribution heterogeneity. Common disturbances in East Timor forests are related to the occurrence of mostly manmade fires, erosion, and community use, e.g., illegal logging, firewood collection, and uncontrolled grazing and agricultural use.

Four circular 1000-m^2 permanent plots were established in June 2002 and tree biometric data were collected: mean basal area 2.34 m^2 (ranging from 2.06 to 2.59 m^2), mean tree height 25.0 m (mean height ranged from 22.0 to 25.6 m), dominant tree height 29.1 m (ranging from 26.2 to 32.9 m), and mean tree diameter at breast height (1.3 m, BH) 42.5 cm (ranging from 37.5 to 43.1 cm). At the time of measurement, trees had no leaves and so the crown diameter could not be measured. The height of the crown ranged from 7.0 to 13.7 m. Sampling was done after plot measurement.

Cores were collected at BH from three trees (two cores per tree in opposite directions) in each plot selected as follows: one tree with a diameter approximately equal to the average plot diameter, and the other two trees corresponding to the mean diameter plus or minus one standard deviation.

Three teak trees could be harvested for destructive wood quality assessment. Tree harvesting is illegal in East Timor and special harvest authorization was obtained from the authorities. The trees were selected from the dominant trees in three plots (one tree per plot), corresponding to about 40 cm BH diameter, on the basis of stem straightness and the absence of apparent defects. The harvested trees had BH diameters of 40.5, 37.9, and 43.5 cm and heights of 25.0, 22.7, and 29.7 m, respectively.

The trees were cross-sectioned at three heights, corresponding to the lower, medium, and upper part of the stem. For determination of ring width, heartwood proportion, and chemical composition, stem disks 5 cm thick were collected at heights of 1.7, 9.5, and 18.7 m. For determination of physical properties, 45-cm-long stem sections were cut immediately below these levels and test samples were prepared from a central board 5 cm thick sawn from these stem sections.

Ring width and heartwood

Cores were mounted in wooden blocks and cross sections were manually polished with progressively finer grades of sandpaper (finishing with P400) until ring boundaries and vessels were macroscopically visible. Disks were polished using a mechanical belt sanding machine. Ring width measurement and ring counting were done using image analysis software (Leica QWin Standard).

The distinction between heartwood and sapwood was performed macroscopically by color difference, and heartwood radius and sapwood width were measured. The heartwood percentage by radius and the number of growth rings in sapwood were determined.

Chemical composition

The delimitation of heartwood was made visually on each wood disk, and samples were taken at different positions evenly distributed along the radius from pith to bark: three samples in the heartwood (inner, middle, and outer positions) and two samples in the sapwood.

Wood samples were ground and sieved, and the 40–60 mesh fraction was kept for analysis. Standardized Technical Association of the Pulp and Paper Industry (TAPPI) methods were used. Total extractives were determined in a Soxhlet apparatus using a solvent sequence of dichloromethane, ethanol, and water (TAPPI 204 um 88). Klason lignin was determined on extractive-free material as the solid residue after total acid hydrolysis (TAPPI 222 om-02; TAPPI). The polysaccharide content was calculated based on the amount of neutral sugar monomers released by total hydrolysis (xylose, glucose, rhamnose, mannose, arabinose, and galactose) after derivatization as alditol acetates. Inositol was introduced as an internal standard before derivatization. Separation was made by gas chromatography and quantification used a previous calibration with pure monosaccharides (TAPPI 249 cm-85; ASTM D 1915). Each chemical determination was made in duplicated samples.

Basic density and shrinkage

Samples were taken from the top end of the central board with dimensions of 4 cm (axial) × 2 cm × 2 cm at three radial positions: 10%, 50%, and 90% of the radius.

Basic density was calculated as the oven-dry mass divided by the saturated volume of the sample, determined using the water-displacement method after 1-week immersion in water, as:

$$\rho = \frac{W_0}{V_s}$$

where ρ is the basic density of the wood (kg/m^3), W_0 is the dry mass (kg), and V_s is the saturated volume (m^3).

Sample dimensions were measured along the radial, tangential, and longitudinal directions using a 0.01-mm precision caliper in saturated and oven-dry conditions. Linear shrinkage was calculated for each direction as the percent dimensional variation from the saturated to the oven-dry condition, and volumetric shrinkage was calculated based on shrinkage in the main directions, as:

$$\beta_L = \left(\frac{(L_s - L_0)}{L_s}\right) \times 100$$

and

$$\beta_V = \left(\frac{(V_s - V_0)}{V_s}\right) \times 100$$

where β_L and β_V are linear and volumetric shrinkages (%), L_s is the dimension of the saturated sample and L_0 is the dimension of oven-dry sample, $V_s = L_t \times L_r \times L_l$ is the saturated volume, and V_0 is the oven-dry volume. Measurements of basic density and shrinkage were done at each sampling point (axial and radial position) in duplicate samples.

Mechanical properties

The mechanical properties were tested using Portuguese standards (NP-619; NP-618) and included the modulus of rupture (MOR) and modulus of elasticity (MOE) determined by static bending and the maximum strength in compression parallel to grain (MCS). Samples were taken from the central board of each height at three radial positions, i.e., 10%, 50%, and 90% of the radius. Samples were conditioned for 1 week at 20º ± 2ºC and 65% ± 5% relative humidity before testing, resulting in test samples with an average moisture content of 11.5%.

Static bending was tested in samples with dimensions of 34 cm (axial) × 2 cm × 2 cm. Tests were performed using an Amsler Universal testing machine and the load was applied in the tangential direction. The span of the bending test was 280 mm and the load speed was set at a constant rate to obtain failure after 3 min. The stress–strain curves were recorded and the modulus of rupture (MOR) (in N/mm^2) and modulus of elasticity (MOE) (in N/mm^2) were calculated as:

$$\text{MOR} = \frac{3PL}{2bd^{10/6}}$$

where P is the maximum load (N), L is the length of sample between the two supports (mm), b is the sample width (mm), and d is the sample thickness (mm), and

$$\text{MOE} = \frac{L^3 \times (P_2 - P_1)}{48I(d_2 - d_1)}$$

where (P_2–P_1) is the load increment (N) in the linear part of the stress–strain curve, L is the sample length between the two supports (mm), (d_2–d_1) is the deflection (mm) corresponding to the load increment (P_2–P_1), and I is the moment of inertia (mm^4).

Samples for compression testing had dimensions of 6 cm (axial) × 2 cm × 2 cm and the load was applied in the axial direction. The maximum crushing strength in compression parallel to grain (MCS) (in N/mm^2) was calculated as:

$$\text{MCS} = \frac{P}{bd}$$

where P is the maximum load (N) and bd is the area of the cross section (mm^2).

Samples with dimensions of 7 cm (axial) × 2 cm × 2 cm, with 2 cm between fixation supports were tested in tension in the axial direction. Measurements of mechanical properties were done at each sampling point (axial and radial position) in duplicate samples.

Results and discussion

Heartwood and sapwood

The heartwood, golden brown and often streaked with grey or black, was clearly distinct from the yellowish-white sapwood. Heartwood accounted for 91%, 90%, and 72% of the stem radius at heights of 1.7, 9.5, and 18.7 m, respectively (Table 1). Similar values were also reported for Indian teak in which heartwood took up 90% of the tree diameter.[14] The sapwood width and number of rings were more regular along the stem circumference and longitudinally

Table 1. Number of rings, average ring width, sapwood width, and heartwood percentage of stem radius of *Tectona grandis* wood

Height level	Average ring width (mm)	Total number of rings	Number of sapwood rings	Sapwood width (mm)	Heartwood (% of radius)
Bottom	3.6 (0.7)	45.3 (7.0)	9.9 (1.0)	16.7 (6.9)	90.7 (4.2)
Middle	3.4 (0.5)	38.8 (5.0)	9.5 (1.1)	13.8 (4.0)	89.9 (3.6)
Top	3.7 (0.7)	19.7 (1.0)	7.1 (1.0)	22.6 (9.1)	72.3 (11.0)

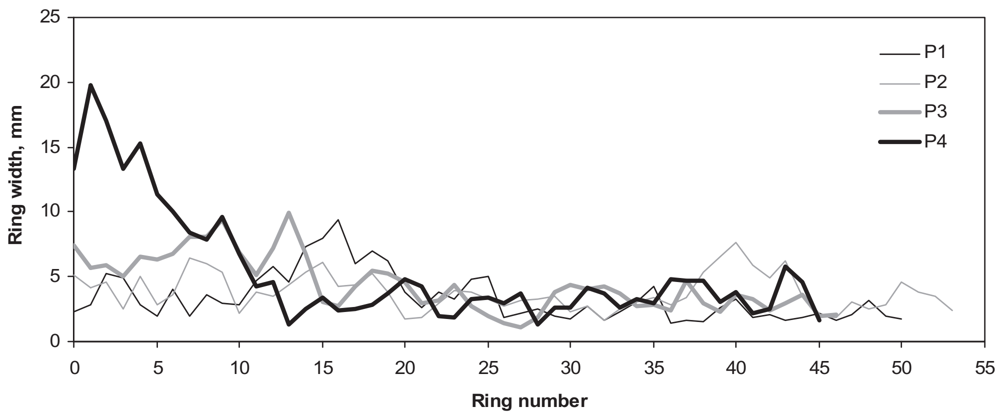
Means and standard deviations (in parentheses) of three trees and three radii per disk sampled at heights of 1.7 m (bottom), 9.5 m (middle), and 18.7 m (top)

Table 2. Mean ring width (mm) for different growth periods of three *T. grandis* trees (one tree per plot)

Tree code	Mean ring width (mm)				
	0–10 years	10–20 years	20–30 years	30–45 years	0–45 years
T2	4.54 (0.86)	4.61 (0.21)	3.96 (0.22)	3.34 (0.14)	3.07 (0.36)
T3	6.40 (0.79)	4.82 (0.38)	3.79 (0.24)	3.58 (0.13)	3.29 (0.39)
T4	7.42 (1.47)	8.67 (0.79)	6.17 (0.64)	5.14 (0.25)	4.51 (0.71)

Means along tree radii from disks from a height of 1.7 m, with standard deviations in parentheses

Fig. 1. Radial variation of tree ring width in *Tectona grandis* trees from four plots (*P1–P4*) measured in cores sampled at a height of 1.3 m. Means of three trees per plot



within the stem (in comparison with heartwood), measuring on average 2 cm and corresponding to nine rings.

This indicates that the formation of heartwood begins early in teak (the samples taken at the top had 20 rings, of which 13 rings were included in the heartwood, Table 1) and that a large heartwood proportion is quickly achieved (72% of the tree radius at the top level with a mean cambial age of 20 years), which is one of the main quality requirements for teak stems.

According to Kokutse et al.,[5] heartwood formation in teak is more dependent on diameter than on age, as also reported previously for other species, e.g., *Acacia melanoxylon*,[15] *Eucalyptus globulus*,[16,17] and *Pinus sylvestris*.[18] In this study, the heartwood proportion was positively associated with tree radius, e.g., relatively more heartwood was present in larger trees, but the limited number of sample trees did not allow further correlations to be established.

Ring width

The mean ring widths measured on disks from 1.7 m above ground level of the harvested trees and in cores from 1.3 m above ground level were 3.6 and 4.3 mm, respectively, and the number of rings ranged from 43 to 50. A large variability in ring width was found along the radius, with some very narrow rings and some very wide rings (extreme values on individual trees were 0.2 and 23.0 mm). Variation around the stem circumference as measured in the three radii was also found, and the interaction between trees in terms of radius was statistically highly significant ($P < 0.001$). This phenomenon occurs frequently in trees that have grown subject to varying conditions of competition and disturbances such as fire or pruning, even without apparent stem defects. The presence of tension wood was not detected.

The first 20 rings were considerably wider compared with rings grown from 30 years onwards (6.1 mm/year for the period 0–20 years, 4.0 mm/year for the period 30–45 years, Table 2). This rapid initial growth of *T. grandis* that slows down after 15–20 years has been reported by several authors, with some variations related to juvenility duration depending on location, site, and individual trees.[19–21]

The influence of plot on the radial ring width pattern was significant (Fig. 1) as a result of the uncontrolled growth differences within the stand during the life of the trees. This means that large variations both in mean ring width and in its radial pattern are to be expected in wood coming from such mature trees in unmanaged forests.

Chemical composition

The mean chemical composition of heartwood and sapwood of *T. grandis* is shown in Table 3, and the radial variation of extractives and structural components are given in Figs. 2 and 3, respectively. Teak heartwood contained more dichloromethane-soluble extractives than sapwood did (4.2% and 1.5% respectively), but the polar compounds content was lower, thereby resulting in similar contents of total extractives in heartwood and sapwood (Table 3). Lignin content and neutral sugar composition were similar in heartwood and sapwood. Xylose was the predominant noncellulosic sugar unit, followed by mannose (8% and 3% of wood).

These results are similar to the few values reported in the literature. Total extractives in heartwood of 29- and 100-year-old *T. grandis* trees were 8.8%–9.4% and 14.1% respectively,[11] while values of ethanol–benzene extractives between 12.4% and 16.0% were reported in 35-year-old trees.[22] Lignin content in 30-year-old trees ranged from 33.3% to 38.3% and the polysaccharide content from 51.5% to 59.3%.[12]

Table 3. Chemical composition of heartwood and sapwood of *Tectona grandis* from northeast East Timor

	Heartwood	Sapwood
Extractives (% of wood)		
Total	10.0 (3.0)	9.2 (1.9)
Dichloromethane	4.2 (2.0)	1.5 (0.7)
Ethanol	4.3 (1.0)	4.8 (1.5)
Water	1.5 (0.4)	2.9 (0.6)
Lignin (% of wood)	32.2 (1.5)	32.4 (1.0)
Carbohydrates (% of wood)		
Total	57.5 (3.8)	56.2 (3.1)
Glucose	44.6 (4.5)	43.7 (3.1)
Xylose	8.3 (2.0)	7.8 (1.2)
Mannose	3.2 (1.0)	3.1 (0.7)
Arabinose	0.6 (0.2)	0.6 (0.2)
Galactose	0.6 (0.1)	0.5 (0.1)
Rhamnose	0.2 (0.1)	0.5 (0.8)

Means of samples from three trees taken at three height levels and different radial positions, with standard deviations in parentheses

Only extractives showed a significant radial variation (Fig. 2). The extractives contents increased from the pith (8.3%) to the heartwood-sapwood transition zone (12.7%), where the maximum content was always found, and then decreased in the sapwood (Fig. 2). This pattern was the consequence of the radial distribution of dichloromethane solubles, which had a peak concentration at the heartwood–sapwood transition (6.0%) and decreased to very small values in the outer sapwood (1.0%). Polar compounds (ethanol and water solubles) increased in sapwood, and the largest concentrations were found closest to the bark.

This radial variation is associated with the metabolic activities observed in the transition zone related to heartwood formation, with enzymatic hydrolysis of triglycerides and an increase in fatty acids during the process of parenchyma cell death.[23] This type of radial variation of extractives has already been reported in other species, e.g., in

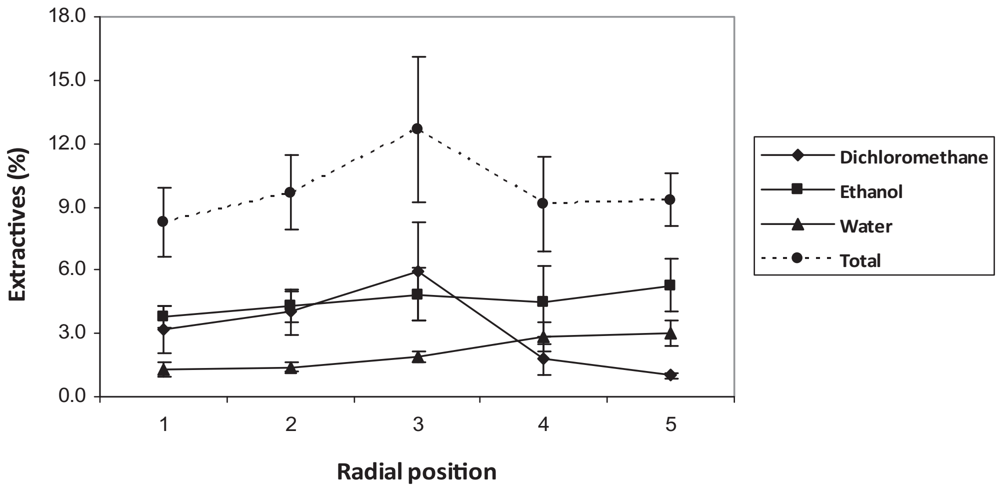


Fig. 2. Radial variation of extractives in *Tectona grandis* trees determined from pith to bark in heartwood (positions *1,2*), in the transition between heartwood and sapwood (position *3*), and in sapwood (positions *4,5*). Mean and standard deviation *bars*

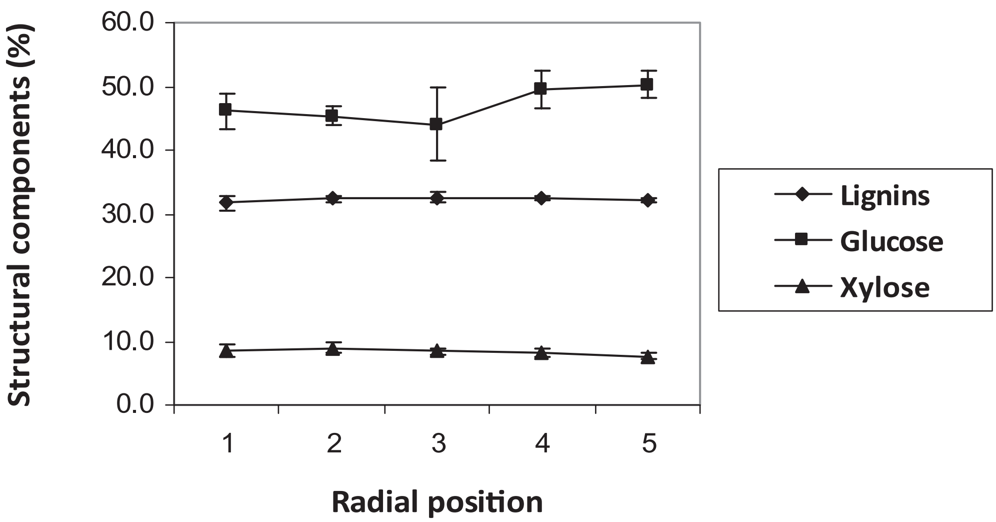


Fig. 3. Radial variation of cell wall structural components in *Tectona grandis* trees determined from pith to bark in heartwood (positions *1,2*), in the transition between heartwood and sapwood (position *3*), and in sapwood (positions *4,5*). Mean and standard deviation *bars*

Table 4. Axial variation of the chemical composition of *Tectona grandis* from northeast East Timor

	Bottom	Middle	Top
Extractives (% of wood)			
Total	9.5 (1.6)	9.4 (1.8)	10.6 (2.6)
Dichloromethane	3.3 (1.2)	3.1 (0.8)	3.8 (1.9)
Ethanol	4.1 (0.6)	4.4 (0.8)	4.9 (0.8)
Water	2.1 (0.3)	1.9 (0.2)	1.9 (0.1)
Lignin (% of wood)	33.4 (0.7)	32.5 (1.1)	30.8 (0.5)
Carbohydrates (% of wood)			
Total	59.2 (2.3)	56.4 (5.6)	58.7 (2.4)
Glucose	46.0 (2.0)	42.2 (5.1)	44.7 (3.2)
Xylose	7.9 (1.1)	8.5 (1.4)	9.6 (1.4)
Mannose	3.9 (1.5)	4.1 (1.2)	3.0 (1.9)
Arabinose	0.6 (0.3)	0.9 (0.6)	0.5 (0.2)
Galactose	0.6 (0.2)	0.5 (0.04)	0.6 (0.04)
Rhamnose	0.2 (0.06)	0.2 (0.05)	0.3 (0.06)

Bottom, middle, and top samples were from 1.7, 9.5, and 18.7 m above ground level
Means of samples from three trees taken at three height levels, with standard deviations in parentheses

Table 5. Mean basic wood density (kg/m^3) of *Tectona grandis* from northeast East Timor at three stem heights and radial variation in cross section from pith to periphery

	Radial position from pith (%)			
	10	50	90	Mean
Bottom	520 (27)	544 (24)	601 (51)	555 (42)
Middle	586 (38)	578 (39)	600 (26)	588 (11)
Top	663[a]	686 (45)	n.d.	674 (13)

Bottom, middle, and top samples were from 1.7, 9.5, and 18.7 m above ground level
Means of duplicate samples from three trees, with standard deviation in parentheses
[a]Only two samples

Fagus sylvatica[24] and *Prunus serotina.*[25] The high concentration of polar extractives in sapwood reflects its physiological conductive function and close proximity to the flux of photosynthetic products in the phloem.[26]

The radial pattern of extractives explains the variation of natural durability in teak wood: the inner heartwood is found to be less resistant to pathogen attack than the intermediate or outer heartwood.[6,27,28] Color, which is closely related to the presence of extractives, was found also to vary radially in teak, with darker colors in the inner heartwood and redness in the outer heartwood.[6]

The axial variation of the chemical composition is shown in Table 4. The extractives content remained relatively constant, with only a small increase at the top. Lignin content was higher in the lower part of the stem and decreased to the top (33.4% and 30.8%, respectively). There was a small axial variation of the glucose content, with a higher value at the bottom in comparison with the top level (46.0% and 44.7%), while the reverse variation was found for xylose (7.9% and 9.6%, respectively). The results of the chemical composition did not show variations that could be linked to the unmanaged status of these stands.

Basic density

The mean basic density of teak wood was 607 kg/m^3 with a range from 579 to 633 kg/m^3 between trees (Table 5). Wood density increased along the stem from 555 to 674 kg/m^3 at the base and top, respectively. There was an increasing radial trend from pith to bark at the stem bottom (on average 520 and 601 kg/m^3 at 10% and 90% from the pith, respectively), but in the middle part of the stem the radial differences of wood density were considerably smaller. The radial increase of basic density toward the bark reflects the smaller ring widths that are found in the outer part of the stem (Table 2).

The results for wood density found in this study are within the range reported in the literature.[10] In Costa Rica teak plantations values between 500 and 650 kg/m^3 at 8 years and between 500 and 600 kg/m^3 at 4 years were reported.[8,9] The mean density at 12% moisture content was 640 and 730 kg/m^3 in natural and plantation teak forests in Bolivia, respectively,[29] and 647, 728, and 779 kg/m^3 for trees of age 11–16, 40–45, and 67–70 years, respectively, in plantations in Togo.[5] In 10- to 34-year-old plantation teaks from Panama, a mean air-dry density of 640 kg/m^3 was found.[13] Bhat and Priya[4] reported air-dry densities from 619 to 682 kg/m^3 and from 655 to 665 kg/m^3, respectively, for 21- and 65-year-old teak plantations in India. Lower values were also reported, e.g., air-dry density between 479 and 591 kg/m^3 for irrigated *T. grandis* trees in India and a specific gravity range of 486 to 539 kg/m^3 for dominant trees from six 60-year-old teak provenance trials.[30] Pérez[31] and Moya and Ledezma[32] concluded that wood density was more related to tree age than to silvicultural management, site, or region, especially in the early plantation stages. This is in accordance with the small differences in wood density that were found for this unmanaged stand and the values given in the literature for plantation trees.

As regards the within-tree variation, there was an overall increase of density with cambial and tree age, corresponding to the radial and longitudinal variations, respectively. In the radial direction, similar results of an increase of density from pith to bark have also been reported for plantation teak by other authors,[7,10] although Bhat et al.[20] observed no significant differences in wood density between young and mature trees.

As regards the longitudinal variation, Pérez and Kanninen[8] found that at the base of large teak trees (DBH greater than 39 cm) the density was lower than that at the beginning of the living crown. This is in accordance with the results obtained here, since the samples taken in the upper part of the stem (top) were located within the living crown. In young 10-year-old teak wood, Moya and Ledezma[32] also reported that density decreased from the base to 50% of total height, but increased thereafter.

Shrinkage

The shrinkage of teak wood from East Timor is presented in Table 6. The average wood shrinkage from saturated to

Table 6. Linear (radial, tangential, axial) and volumetric wood shrinkage, modulus of rupture (MOR), modulus of elasticity (MOE) measured in static bending, and maximum strength in compression parallel to grain (MCS) of *Tectona grandis* from northeast East Timor measured in three radial positions from pith to bark

	Radial position from pith to bark (%)			
	10	50	90	Mean
Radial shrinkage (%)	3.55 (0.90)	3.26 (0.72)	3.66 (1.24)	3.50 (0.97)
Tangential shrinkage (%)	4.67 (0.96)	5.00 (1.09)	5.99 (1.14)	5.17 (1.38)
Axial shrinkage (%)	0.40 (0.06)	0.44 (0.04)	0.57 (0.32)	0.49 (0.33)
Volumetric shrinkage (%)	6.97 (1.19)	7.83 (1.54)	7.65 (1.44)	7.60 (1.64)
MOR (N/mm^2)	135 (18)	141 (22)	146 (18)	141 (19)
MOE (N/mm^2)	10330 (2248)	10654 (2165)	10931 (1762)	10684 (2028)
MCS (N/mm^2)	50 (4)	52 (8)	45 (8)	50 (8)

Means of samples from three trees and three heights, with standard deviations in parentheses

the oven-dry state was 3.5% and 5.2% for the radial and tangential directions, respectively, and 7.6% for volumetric shrinkage. The coefficient of anisotropy (ratio of tangential to radial shrinkage) was small at 1.48, indicating a low risk of deformation in wood during drying.[33] There was very little radial variation of shrinkage, with a slightly increasing trend of the tangential shrinkage from pith to bark (from 4.7% to 6.0%), reflecting the relationship between wood shrinkage and density.[33]

The small dimensional variation found for teak wood from East Timor agrees with the values reported for teak from other origins and confirms the prized dimensional stability of teak wood. Baillères and Durand[10] reported a range of 5.7%–8.4% for the volumetric shrinkage of teak wood from natural forest trees, and Moya and Ledezman[32] also reported a volumetric shrinkage of 6.5%–7.5% for 10-year-old teak trees from plantations, quite similar to the values obtained here.

Mechanical properties

The mechanical properties of teak wood from East Timor (Table 6) are similar to values reported for teak wood from other origins. The average MOE values of 10684 N/mm^2 were similar to those published previously by Baillères and Durand[10] for teak wood of different origins ranging from 7848 to 16579 N/mm^2, and by Posch et al.[13] for wood from Panama (14200 N/mm^2). Bhat and Priya[4] reported 8436–13643 and 12512–17580 N/mm^2 for 21- and 65-year-old plantation teaks from India, respectively.

The mean bending strength (MOR) of 141 N/mm^2 is somewhat higher than the values reported for teak wood of other origins, e.g., 105 N/mm^2 in Panama,[13] and 81.0–135.9 N/mm^2.[10] Bhat and Priya[4] reported values of 133.2 and 91.8 N/mm^2 for slow- and fast-growth trees in 21-year-old plantations, and 136.1 and 103.8 N/mm^2 for slow- and fast-growth 65-year-old trees.

The mean compressive strength (MCS) was 50 N/mm^2. This value is similar to those given in other reports, e.g., 50[13] and 44.4–65.9 N/mm^2.[10] Values of 44.6 and 53.9 N/mm^2 for slow- and fast-growth 21-year-old plantation trees and 48.0 and 59.0 N/mm^2 for slow- and fast-growth 65-year-old trees were also reported.[4]

As regards the effect of the radial position on mechanical properties, teak wood showed negligible differences along the radial direction despite the differences in density between the inner and outer parts of the stem. Several authors have also found that differences in mechanical and physical properties of juvenile wood and adult wood in teak were negligible.[10] However, others have found higher MOE values in adult wood: Bhat et al.[20] reported 12695 and 15746 N/mm^2 in juvenile and mature wood in 63-year-old plantation teaks, and Kokutse et al.[5] reported 13163 and 16704 N/mm^2, respectively, in 6- and 70-year-old plantation teaks and observed a significant MOE increase with cambial age.

Conclusions

Teak wood from mature *Tectona grandis* trees from an unmanaged stand in East Timor showed favorable quality parameters (a large proportion of heartwood and adequate physical and mechanical properties) that were similar to the values reported for teak trees from plantations and other origins.

The disturbances on individual tree growth arising from the unmanaged status of the stand, e.g., uncontrolled fires and tree pruning and thinning by local communities, are evidenced by the within-tree variability of ring width and consequently on wood density. However, the longitudinal and radial variations were of low magnitude and in a degree that did not negatively impact on timber quality.

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