

Anatomical variation of teakwood from unmanaged mature plantations in East Timor

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Abstract Teak (*Tectona grandis* L. f.) is an important native species of Southeast Asia, producing an excellent quality wood with high demand in the world market contributing positively to development and economic growth of the countries. There are few published studies on the anatomical variability of teak wood from East Timor. The wood anatomical characterization and its within-tree variation were studied in three axial and radial positions of trees from an unmanaged pure stand. The wood is semi-ring-porous to ring-porous. The vessels are solitary and grouped, with 206 and 89 μm diameter (earlywood and latewood) and 259 μm length. Axial parenchyma is paratracheal unilateral and marginal. Rays are homocellular and heterocellular, varying between 241 and 1293 μm in height. Fibers, the most abundant tissue (52 %), had a mean fiber length, width and wall thickness of 1.15 mm, 28 and 6 μm , respectively. The anatomical features of teak wood differ from those reported for other origins in considerably smaller vessels and thicker walled fibers.

Longitudinal variation showed a decrease of vessel area, fiber size, and an increase of vessel frequency, parenchyma and ray proportions towards the top of the tree. Radially vessel size, fiber length and wall thickness tended to increase with cambial age.

Keywords Anatomy · Cell size · Within-tree variability · *Tectona grandis* · East Timor

Introduction

Teak (*Tectona grandis* L. f.), first formally described by Carl Linnaeus the Younger (1782), occurs in natural forests of India, Thailand, Myanmar and Laos, and was successfully introduced into other tropical and subtropical regions in Australia, Africa and Latin America, owing to its easy plantation establishment and high resistance to diseases and fire [1].

Teak occurs in East Timor (“Timor Leste” in Portuguese), that was originally dominated by forests, but their area was reduced and modified during the more than four centuries of Portuguese colonial dominance and the following occupation by Indonesia [2]. The forests occupy now approximately 507,000 ha that represents 34.3 % of the land area, and comprises tropical and subtropical moist mountain forests [3] e.g., *Eucalyptus alba* Reinw. ex Blume, *E. urophylla* S. T. Blake, *Tamarindus indicus* L., *Pterocarpus indicus* Wild., *Toona sureni* (Blume) Merr., *T. grandis*, *Santalum album* L. and *Casuarina equisetifolia* L., some of which are endangered due to extensive deforestation [4].

Teak is a very valuable species for sawn timber and round wood. The world production of teak wood is estimated at 3 million m^3/year of which 90 % is in

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Asia, but the current demand is higher [5]. Therefore, teak became an important plantation species for tropical forestry, mostly under intensive short rotation management.

The wood of *T. grandis* is well known for its durability, strength and esthetic beauty and is considered as one of the most valuable woods in the world. Teak is a multi-purpose wood, i.e., structural timber, flooring, boat building, veneer, musical instruments and carvings [6]. Teak wood has a medium specific gravity, strength and dimensional stability [7, 8], corrosion resistance and easy processing with good seasoning performance, and reputed for its excellent weathering and decay resistance [9].

There is a general agreement that teak growth and wood properties vary according to location, provenances and silviculture i.e., natural forests or short rotation and fast growing trees [5, 10–12]. Research has addressed the effect of tree age and provenance on growth rate, ring structure and heartwood proportion [13–15], density [16, 17] and wood color [18–20]. *T. grandis* is also one tropical species used for dendrochronological purposes due to its favorable anatomical structure [21–24].

There are some general reports on the wood anatomy of *T. grandis* [13, 25–27] but there is limited information on wood variability regarding its anatomical patterns of variation, which may have a large influence on the processing and product performance [28, 29].

There are also very few published studies on the anatomical variability of teak wood from East Timor. The present study complements the previous research on the wood of *T. grandis* from East Timor, first conducted by Freitas [7] on anatomy, and recently by Miranda et al. [30] on chemical composition and properties and by Sousa et al. [31] on ring width and heartwood development. In this study, a detailed anatomical characterization of teak wood was made including the within-tree and between-tree axial and radial variation of fiber and vessel biometry, and tissue proportion. It is the objective of the present study to characterize important teak wood anatomical features for wood quality, thereby sustaining a continuing valorization of *T. grandis*.

Materials and methods

Teak trees with about 70 years of age were felled from an unmanaged stand in the Northeast of East Timor, in the Lautem district between Los Palos and Fuiloro (08°30'S–126°59'E, mean altitude 380 m). The climate is characterized by distinct wet and dry seasons determined by monsoon influence. The average yearly temperature is 23.8 °C and rainfall is 1924 mm. Peak rainfall occurs from May to June, and the dry season is August–October (mean

monthly rainfall 32 mm), while July and November are transition months (125 and 94 mm, respectively).

Sampling was carried out in 2003, in a pure teak stand of 3.76 ha with 4 m × 2 m spacing established in the period 1940–1950 (under the Portuguese administration). The stand by the time of sampling had on average 165 trees/ha, 25 m of tree height and 43 cm of diameter at breast height (DBH). The soils are of medium texture and pH 7.2, and the site has a declivity of less than 5 %. No further records on stand establishment and management practices were available, as described by Sousa et al. [31].

Since teak harvesting is illegal in East Timor, a special authorization was given by the Ministry of Agriculture to fell a restricted number of trees. Three trees were selected based on dominant trees of DBH class 40 cm and stem straightness with no apparent defects. The mean DBH of the harvested trees was 47 cm and mean tree height was 27 m.

A 5-cm-thick cross-sectional disc from each tree was sampled at three height levels: 1.7, 9.5 and 18.7 m. The transverse surfaces of each disc were polished with sandpaper with different grits (180, 320, 400 and 600).

Three radial strips from pith to bark were randomly selected with approximate equal distribution around the cross-section. To better distinguish the vessels, white wax crayon was used. Sequential images were taken from pith to bark using a video camera JVC model TK-C11380E (Japan) connected to a low power microscope Olympus SZH10 (Japan). The number and width of rings, number of vessels per ring, and vessel area were measured using the software Leica Qwin Standard (United Kingdom) following the methodology proposed by Leal et al. [29].

For anatomical characterization, wood cubes (2 × 2 × 2 cm³) were prepared along the three radial positions e.g., near the pith, middle and near the bark (radial variation) at three height level e.g., base, middle and top of the tree (axial variation). The wood blocks were softened by boiling in water, and transverse and longitudinal microscopic sections (approximately 17 μm thick) were prepared with a sliding microtome Leica SM2400 (Germany). The sections were stained with safranin (Merck) and mounted in Eukit (Panreac).

Wood macerations were carried out using glacial acetic acid (Panreac) and 30 % hydrogen peroxide (Scharlau) (1:1 ratio), at 60 °C for 48 h. The macerated tissue was washed in running water until free of all acid traces and stained with astra blue for determination of vessel element length and fiber biometry.

Thirty measurements were taken for vessel length and diameter, and ray height and forty for fiber length, width and wall thickness. A Leica DMLA microscope connected to a video camera Leica DFC320 (Germany) was used to

acquire images which were stored in JPEG graphic format using the image analysis software Leica Qwin Standard (United Kingdom). The frequency of rays (number of rays per square millimeter) was determined by counting individual rays present in ten randomly selected microscopic fields. For determining the size of intervacular pits, 10 measurements were taken according to Angyalossy-Alfonso and Miller [32].

The proportion of tissue types was calculated in the transverse section on five randomly selected areas using the image analysis system coupled to a microscope; a grid with of 48-points was placed over each image and tissue types (fiber, parenchyma, vessel and ray) were counted and converted in a percentage of the total area, following Quilhó et al. [33].

The overall means were calculated from the means of individual samples and an ANOVA procedure was performed using SPSS 19.0 software IBM (USA) to determine whether there were significant differences between the anatomical variable of wood.

Descriptive anatomical terminology followed the IAWA List of Microscopic Features for Hardwood Identification [34].

Results and discussion

Teakwood shows a clear distinction between sapwood and heartwood: the former pale yellowish or grayish and, heartwood golden brown with dark streaks (Fig. 1a). The sapwood was narrow, with an average radial width of 18 mm, regular along the stem circumference.

Growth rings were distinct, delimited by large early-wood vessels and marginal parenchyma (Fig. 1b). Often wedging rings were also present. Mean ring width was 3.6 mm and overall similar with teak growth in other world regions over the same growth period [31].

The wood texture is medium to coarse and the grain is straight, sometimes wavy. The wood figure is given by the distribution of the parenchyma and large vessels in the beginning of the growth rings, and from the contrast between the rays and the fibrous tissue (Fig. 1b–d).

Anatomical features

Figure 2 shows the anatomical structure of teakwood, and Table 1 summarizes the cell dimensions and proportion of tissues in the studied trees.

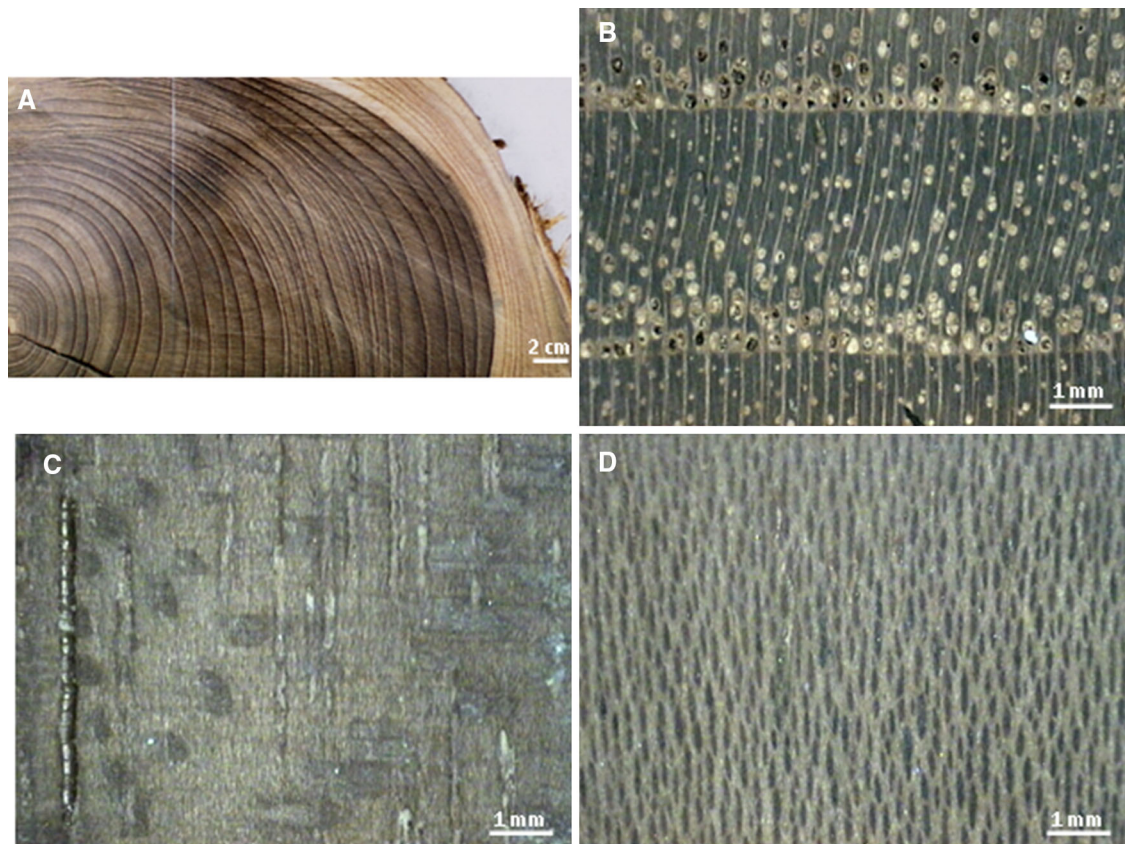


Fig. 1 General observations of wood of mature trees of *Tectona grandis* from East Timor. **a** Cross-sectional surface, **b** transversal, **c** radial and **d** tangential wood sections

Growth rings The wood is semi-ring-porous to ring-porous (Figs. 1b, 2a).

Vessels The vessels are solitary and in short radial multiples of 2–3 (more frequent in latewood) (Figs. 1b, 2a); occasionally filled with thin-walled tyloses (Fig. 2d) and yellowish-white deposits. They are almost circular to oval in outline with an average tangential diameter of 206 μm in the earlywood (80–382 μm minimum and maximum) and 89 μm in the latewood (45–196 μm minimum and maximum) and vessel elements are 259 μm in length. The transition from earlywood to latewood is gradual. Vessels occupied 12 % of the ring area, corresponding to an average of 9 vessels/ mm^2 . Perforations are simple (Fig. 2e). Intervessel pits numerous, alternate, 5–9 μm diameter, pits leading to contiguous ray numerous to each ray cell (Fig. 2e).

Parenchyma Axial parenchyma is scanty (14 % of the tissues), unilateral paratracheal, paratracheal-zonate

parenchyma, marginal confined to the earlywood, 2–3 cells wide, demarcating the growth ring boundary (Fig. 2a). The axial parenchyma is not storied, with 3–4 cells per parenchyma strand.

Fibers Fibers represented about 52 % of the wood cross-sectional area. They are coarse, strongly angled in the transverse section and not aligned in radial rows, thin to medium with 1.15 mm (0.90–1.52) length, 28.4 μm (22.6–35.7) width and 6.1 μm (7.8–4.4) wall thickness. Fibers are septate and non-septate, sometimes bifurcated. Pits are numerous, confined to the radial walls, simple to minutely bordered. Fibers with small oil droplets were observed in tangential and radial sections. Vascular tracheids are also present (Fig. 2f).

Rays Rays occupied 18 % of the wood cross-sectional area. The rays were (2–) 3–4 (–6) cells wide (Fig. 2b), homocellular with procumbent cells (Fig. 2c) and heterocellular with one row of square marginal cells. Rays are not storied, 643 μm

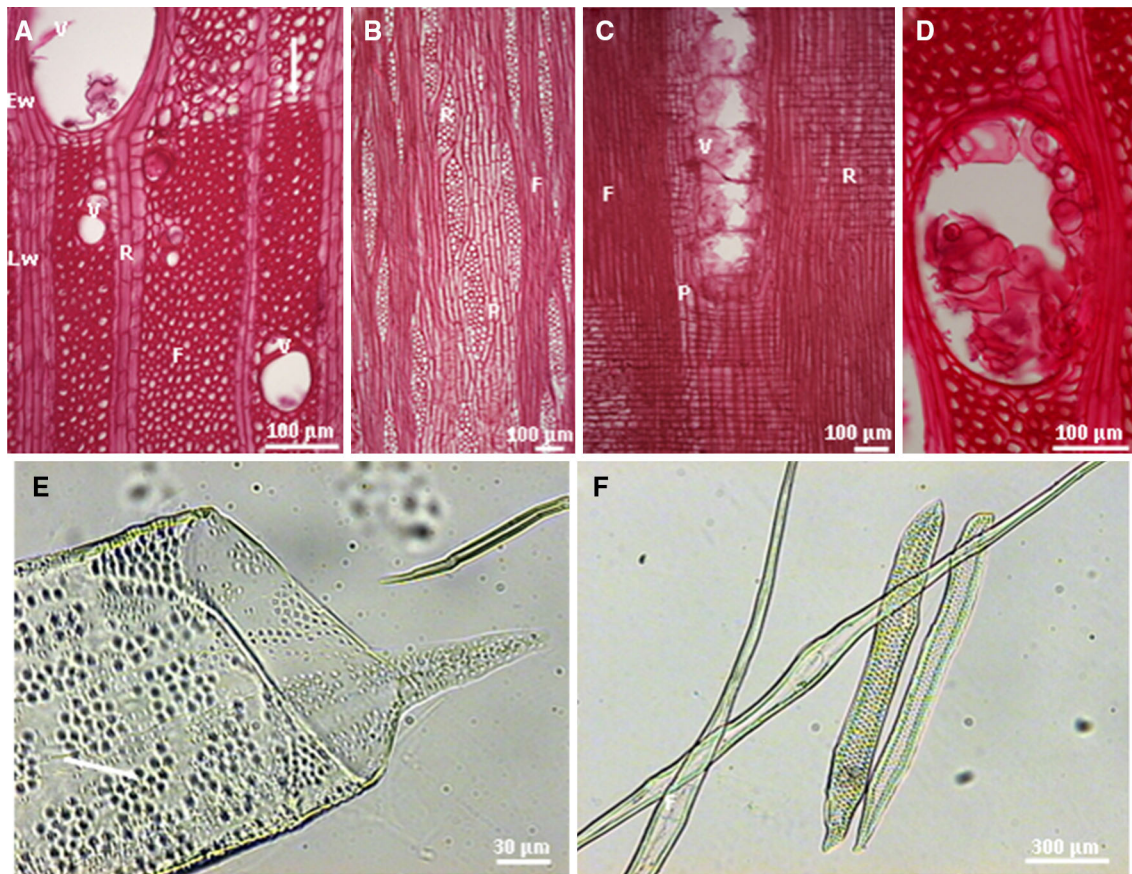


Fig. 2 Transversal, tangential and radial sections and macerated of *Tectona grandis* wood. **a** Transition from earlywood (Ew) to latewood (Lw) marked by marginal parenchyma (arrow) and slight dilatation of the ray (R); vessels (V) solitary in earlywood and radially grouped in latewood; fibers (F) with small lumen and thick walled in the latewood (transversal section); **b** biseriate and multiserial rays (R); fibers (F) and axial parenchyma (P) with 2–4 cells per parenchyma

strand (tangential section); **c** rays (R), fibers (F), vessel elements (V) and axial parenchyma (P) (radial section); **d** vessel with tyloses (transversal section); **e** earlywood vessel element with terminal simple perforation and alternate pits (arrow) (macerated); **f** libriform fibers (F); vascular tracheids with numerous pits (macerated)

Table 1 Mean wood anatomical characteristics of three trees of *Tectona grandis* from East Timor

Features	Tree 1	Tree 2	Tree 3
Tissue proportion (%)			
Parenchyma	16	13	13
Vessel	12	11	13
Ray	16	17	21
Fiber	52	54	49
Fibers			
Length (mm)	1.07	1.22	1.16
Width (μm)	27.9	28.6	28.8
Wall thickness (μm)	5.9	6.0	6.4
Lumen diameter (μm)	16.5	16.9	16.3
Vessels			
Tangential diameter (earlywood) (μm)	220.5	202.5	194.2
Tangential diameter (latewood) (μm)	81.5	91.7	92.8
Length (μm)	271	252	254
Mean area (μm^2)	16,683	19,339	17,801
Number of vessels per mm^2	9	7	10
Intervessel pit diameter (μm)	7	6	6
Rays			
Ray height (μm)	741	565	622
Number of rays per mm^2	10	9	11

high with 21 cells height and an amount of 10 rays per mm^2 . Small oil droplets were observed in ray cells.

ANOVA revealed significant variation in fiber proportion and length, vessel frequency and rays ($p < 0.05$) between the studied trees.

In general, the wood anatomical structure of the studied trees is in accordance with previous descriptions for the species [7, 8, 26, 27, 31, 35, 36]. Teakwood is well known to have a ring-porous nature or semi-ring-porous pattern [37]. The earlywood pores are distinctly larger than those in the latewood and mark the growth ring boundaries, which give rise to the patterns that are so appreciated in teakwood [15]. Also contributing to the teak wood esthetical properties are the thick-walled fibers in latewood and the marginal paratracheal-zonate parenchyma, which are also good markers of growth ring as in other tropical species [38].

In the literature, there are several reports regarding cell biometry of teakwood, and it is notorious that there is substantial variation between determinations of different authors and the values of the present study, although the studied samples often corresponded to different tree growth and ages.

In studied trees, the tangential diameters of earlywood and latewood vessels were lower compared with determinations by various authors e.g., 225.8 and 100.9 μm in earlywood and latewood, respectively [38]; 140–270 μm in

earlywood, 50–100 μm in latewood [36]; 228 μm in earlywood, 112 μm in latewood [37] or 340–370 μm in earlywood and 20–290 μm in latewood [26].

The length of the vessel elements is similar to the few reported values: 279 μm [39], 250 μm [7] and 244 μm [8]. The vessels were more abundant compared to other reported values of 4–9 vessels/ mm^2 [36], 6 vessels/ mm^2 [39], 2–6 vessels/ mm^2 [7] and 4–8 vessels/ mm^2 [8].

The intervessel pit diameter of 6 μm in the studied trees is larger than other reported values of 3–5 μm [8], but similar to 5–7 μm [26] and 6 μm [7, 35, 36, 39].

This variation in the vessel biometry is indicative of the adaptation of teak to local growth conditions, mainly rainfall and water availability, or by inheritance as suggested by Nocetti et al. [15] and is certainly of factor contributing to the high adaptability of teak to several environments.

The fiber length of the studied trees is in the range of those reported in the bibliography: 1.20 and 1.24 mm [7, 8], 0.70–1.40 mm [26], 0.90 mm (1.20–1.30 mm) [35], 0.70–1.40 mm [36], 0.70–1.60 mm [17] and 1.22 mm (0.82–1.65 mm) [37]. The average fiber width of 28 μm is similar to the values reported by Josue and Imiyabir [37], Moya et al. [17] and Freitas [7] of, respectively, 35 μm (27–46 μm), 21–29 and 25 μm , and larger than the 15 μm (17–20 μm) reported by Tewari [35].

The fiber wall thickness and lumen diameter were on average 6.1 and 16.6 μm , respectively, which were higher than the values of 3.6 and 4.0 μm , 4.0 and 3.2–5.7 μm reported by Freitas [7], Tewari [35] and Moya et al. [17], respectively. The diameter of fiber lumen was in the range of the 11–20 μm reported by Moya et al. [17].

Fibers were the most abundant tissue in wood i.e., 52 % of the cross-sectional area close to 60–64 % determined by Bhat and Priya [40]. The mean proportion of axial parenchyma of 14 % was lower compared with the values reported by Bhat and Priya [40] i.e., 24–31 and 26–27 % in 21- and 65-year-old plantation, respectively.

Josue and Imiyabir [37] reported similar frequency of rays with values of 5–14 per mm^2 , while Richter and Dallwitz [36], Phengkklai et al. [26] and Freitas [7, 8] referred a lower frequency of 5–7, 4–7, 2–6 and 4–7 per mm^2 , respectively, and Moya et al. [17] reported a higher frequency between 15 and 34 per mm^2 . The height of rays was on average 643 μm higher than the available data from literature e.g., 29–90 μm [17], 301 μm [8], 400 μm [35], and similar to 659 μm [37] and 500–1000 μm [36].

Axial variation

The number of vessels per mm^2 varied axially with an increasing frequency of vessels towards the top, while the

Table 2 Axial variation of anatomical properties of *Tectona grandis* trees from East Timor measured at three stem height levels

Features	Height level		
	Base	Middle	Top
Tissue proportion (%)			
Parenchyma	10	16	17
Vessel	12	14	11
Ray	19	13	22
Fiber	55	53	47
Fibers			
Length (mm)	1.20	1.15	1.02
Width (µm)	29.5	27.9	26.6
Wall thickness (µm)	5.9	6.3	6.1
Vessels			
Tangential diameter (earlywood) (µm)	223.4	216.5	177.2
Tangential diameter (latewood) (µm)	92.8	89.6	83.4
Length (µm)	241	260	275
Mean area (µm ²)	17,695	21,657	10,750
Number of vessels per mm ²	9	8	10

proportion of vessels tended to increase from base to middle and then decreases to the top (Table 2). The height level was a statistically significant ($p < 0.05$) source of variation for the frequency of vessels but was not significant for the proportion of vessels.

The average vessel area and tangential diameter of vessels (earlywood and latewood) decreased from base to the top, while vessel length increased from base to top (Table 2).

The decrease of vessel area and proportion with the concomitant increase of vessel frequency from base to the top of the tree has been reported by Fichtler and Worbes

[41] in tropical trees, although the vessel proportion was quite variable and influenced by ring width differences. This was not the case in the studied trees for which Sousa et al. [31] showed a small and insignificant axial variation of ring width.

The proportion of parenchyma and rays increased to the tree top, although not linearly i.e., rays proportion decreased from base to middle and then increased for the top (Table 2). For these anatomical characteristics, the height level interaction was significant ($p < 0.05$).

The fiber proportion and dimensions (length and diameter) decreased with tree height and fiber wall thickness remained constant (Table 2), but the differences were only statistically significant for fiber length and diameter ($p < 0.05$).

The same trend of variation was found in 15-, 20- and 25-year-old trees from Nigeria [42] and in 15-year-old trees from Malaysia [37], and justified by the influence of auxin that promotes rapid production of cells with decreasing maturation time resulting in the production of smaller cells at the tree top.

Radial variation

The radial variation of the anatomical characteristics of teak wood is summarized in Table 3. Overall, the proportion of tissues did not change radially, a feature that contributes to the homogeneous appearance of teakwood.

The area and tangential diameter of vessels of earlywood increased radially especially from the inner position near the pith to mid-radius. This is in accordance with results of Moya et al. [17] and Palakit et al. [43], but not with Lima et al. [44] who found a radial decrease of vessel

Table 3 Radial variation of anatomical properties of trees of *Tectona grandis* from East Timor, measured at three radial positions

Features	Radial position		
	Pith	Middle	Periphery
Tissue proportion (%)			
Parenchyma	14	13	15
Vessel	13	11	13
Ray	16	21	18
Fiber	53	51	50
Fibers			
Length (mm)	1.08	1.16	1.21
Width (µm)	27.6	29.1	28.3
Wall thickness (µm)	5.4	6.1	6.7
Vessels			
Tangential diameter (earlywood) (µm)	193.8	209.6	213.9
Tangential diameter (latewood) (µm)	89.2	90.7	86.4
Length (µm)	263	255	258
Mean area (µm ²)	13,430	19,175	20,876

diameter. On the other hand, the vessel length tended to decrease from pith to periphery (Table 3).

Bhat et al. [13] observed in 63-year-old trees that the vessel diameter stabilized around 20 years after an initial increase during the juvenile phase of growth and in contrast vessel percentage increased more after 20 rings resulting in higher vessel percentage at about 60 years. A decrease of vessel frequency with age in the juvenile phase was mentioned by Moya et al. [17] for 13-year-old *T. grandis*. The constant proportion of vessels was observed by Rahman et al. [45].

Fiber length and wall thickness increased from pith to the periphery of trees with significant differences between radial positions ($p < 0.05$). The fiber diameter increased from pith to middle and then decreased somewhat from mid-radius to the periphery (Table 3). These results are comparable with other studies on teak [42, 44]. In general, there is a general increase of fiber length due to the length increase of cambial initials with increasing cambial age [46, 47]. A decrease of ray frequency with age was mentioned by Moya et al. [17] and Lima et al. [44].

In conclusion, this study revealed that the anatomical features of teakwood from an unmanaged mature stand in East Timor were similar to those reported for teakwood of other origins with some exceptions: the studied trees showed lower vessel diameter and thicker fibers than those reported in the literature. There was considerable homogeneity between the trees and within the trees. The longitudinal variation of wood anatomy was minimal but towards the top of the tree there was a decrease of vessel area, fiber dimension, vessel and fiber proportion, and an increase of vessel frequency, parenchyma and rays proportions. The radial variation was also small with an increase of vessel size fiber length and wall thickness with cambial age.

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