European Journal of Wood and Wood Products (2024) 82:357–369
https://doi.org/10.1007/s00107-023-02031-5

ORIGINAL ARTICLE

Heartwood proportion and density of *Tectona grandis* L.f. wood from Brazilian fast-growing plantations at different ages

Kezia Rage Curvo[1,2] · Gabriel Afonso Oliveira Silva[1] · Vinícius Resende Castro[2] · Fernando Henrique Gava[1] · Bárbara Luísa Corradi Pereira[1] · Aylson Costa Oliveira[1]

Received: 19 April 2023 / Accepted: 1 December 2023 / Published online: 5 January 2024

Abstract

The high demand for teak wood has driven efforts to achieve increased volumetric production in fast-growing plantations. However, the logs often exhibit higher proportions of sapwood and juvenile wood. This study was conducted to investigate how the age of teak trees in commercial plantations influences the heartwood proportion, wood density, and formation of mature wood. A total of 12 trees of both clonal and seed origins were harvested at the ages of 5, 10, 15, and 20 years old. Disks in the regions of the base, 2.3 m, and top of the trees were collected. Along the stem, we determined the total, heartwood, and pith diameters, as well as the proportions of bark, sapwood, heartwood, and pith. The base disks were used to analyze wood density and to demarcate the transition from juvenile to mature wood stages by X-ray densitometry. As teak wood aged, it exhibited higher heartwood percentages, with variations ranging from 7% (5 years old) to 56% (20 years old). The five-year-old wood had the mean highest density (0.74 $g.cm^{-3}$). There was a trend of increasing mean wood density as the trees aged from ten years. The diameter profiles by X-ray densitometry indicate a higher wood density in the pith-bark direction. The density of 20-year-old wood ranged from 0.54 $g.cm^{-3}$ (ring 1) to 0.78 $g.cm^{-3}$ (ring 19). For all ages evaluated, juvenile wood is predominant, with the transition age occurring at approximately 11 years old. However, only 15- and 20-year-old trees had mature wood in their heartwood, but it was less than 2% of the total heartwood at those ages.

1 Introduction

Teak wood (*Tectona grandis* L.f.) stands out in the global market for its aesthetic features, especially heartwood, which is known for its high natural durability and good dimensional stability (Lopes et al. 2014). Its versatility extends to a multitude of applications, including use in construction, shipbuilding, and the crafting of luxury furniture (Blanco-Flórez et al. 2015).

Teak is native to the tropical forests in Southeast Asia, where it is exploited in plantations aged between 60 and 100 years old (Giustina et al. 2017). However, the high demand for teak wood combined with the lack of supply caused by its long rotation has led the wood industry to face difficulties in supplying consumer market demand (Damayanti et al. 2019). These endeavors prioritize achieving greater volumetric production within fast-growing plantations. However, it is worth noting that the wood produced is typically regarded as having a moderate quality, primarily attributed to its lower heartwood/sapwood ratio, smaller diameter, less uniform color and lighter coloring than native teak (Gava et al. 2021; Moya and Tenorio 2021).

In this context, Brazil has introduced several commercial teak plantations, highlighting the state of Mato Grosso since the species is highly adaptable to the region (Rocha et al. 2015). In addition to favorable conditions of soil and climate, the application of adequate and intense forestry management favored a shorter teak production cycle with final harvesting by 25 years (Rosa et al. 2017). However, a number of Brazilian companies have been progressively shortening the rotation period for teak plantations, aiming for final harvesting between eighteen and twenty years old. The primary market for this wood is exported to Asia, particularly India, in the form of unprocessed logs and rough-sawn timber (Takizawa et al. 2022). As a result, it is crucial to conduct studies that assess the wood properties of Brazilian

✉ Kezia Rage Curvo
kezia.rage@hotmail.com

1 Graduate Program in Forest and Environmental Sciences, Forest Engineering Faculty, Federal University of Mato Grosso, Cuiabá, Mato Grosso, Brazil

2 Department of Forest Engineering, Federal University of Viçosa, Viçosa, Minas Gerais, Brazil

teak plantations with shorter rotation periods, especially at various ages, to ascertain the quality of the produced wood.

Furthermore, the utilization of superior genetic material has substantially enhanced the performance of teak plantations in comparison to the initial seed introductions in Brazil. Clonal plantations exhibit notable advantages, including increased mean diameter, basal area, and enhanced planting uniformity. These characteristics significantly contribute to streamlined industrial operations and higher lumber yields. Notably, clonal teak stands out for its relatively high heartwood proportion, making it a preferred choice in the lumber industry (Lemos et al. 2019; Berrocal et al. 2020; Moya et al. 2020; Reategui-Betancourt et al. 2020; Barrantes-Madrigal et al. 2021). As a result of these desirable attributes, extensive research has been dedicated to the study of heartwood formation, variation, and measurement in trees cultivated under fast-growth conditions (Moya et al. 2020).

Teak heartwood formation begins between four and six years old and becomes noticeable by color differentiation from sapwood (Moya et al. 2014). Studies show that heartwood formation is positively related to increasing tree diameter and age (Moya et al. 2020; Berrocal et al. 2020; Hao et al. 2022); that is, the percentage of heartwood is influenced by the growth rate. It is therefore important to study the variation in heartwood as forest plantations age to comprehend how the percentage increase and the volume of heartwood change until the final harvesting age. Heartwood is the commercially valuable part, while sapwood is closely related to waste production (Yang et al. 2020; Silva-Albuês et al. 2024).

The teak fast-growing plantations involving increasingly shorter rotation cycles provide the market with trees of the desired commercial dimensions. However, these plantations have also introduced market products with large proportions of sapwood and juvenile wood (Richter et al. 2003; Paes et al. 2015). Compared to mature teak wood, juvenile wood has shorter fibers with wider diameters, thinner cell walls, a higher microfibrillar angle, a lower percentage of latewood, lower wood density, lower dimensional stability, lower biological resistance, and lower mechanical strength and stiffness (Bhat and Florence 2003; Darmawan et al. 2015; Delucis et al. 2014), which are not desirable by the wood industries that process teak logs into lumber.

Therefore, defining the pith distance to the transition from juvenile to mature wood, as well as the age at which such a transition occurs, has become an alternative to soften the negative impact of juvenile wood and select trees with greater heartwood proportions and mature wood (Darmawan et al. 2015). It is worth highlighting that both juvenile and mature wood are formed throughout the growth of teak. Therefore, the more advanced the age of the trees is, the larger the heartwood proportion (Miranda et al. 2017), although the heartwood of teak trees does not have uniform properties in its central region, as there is a large amount of juvenile wood (Moya et al. 2014).

In addition, age influences the physical properties of wood, reflecting its technological behavior and hence its industrialization process. Thus, density is related to other important quality parameters, such as anatomical, chemical, and physical–mechanical properties, in addition to varying according to both the age and position within the tree, from pith-to-bark and base-to-top (Canal et al. 2020). Teak wood from fast-growing plantations has an average density range of 0.50–0.60 g.cm^{-3}, which varies depending on the growth site and has a tendency to increase with age (Chagas et al. 2014; Berrocal et al. 2020; Lima et al. 2021). In addition, wood density varies within the growth ring and in the radial direction (Gaitan-Alvarez et al. 2019). Wood density is a key parameter in assessing wood quality, as its value helps define the most appropriate wood applications (Dias et al. 2018; Rios et al. 2018).

Therefore, the aim of this study was to evaluate the stem morphology, heartwood formation, and wood density of fast-growing teak from commercial plantations in Brazil within trees aged between five and twenty years old. Using the X-ray densitometry technique, we sought to determine, through the radial profile of wood density and growth ring width, the age of transition from juvenile to mature wood. This information might help industries learn the ideal final harvesting age to produce trees with adequate volumes and satisfactory technological properties.

2 Material and methods

2.1 Sample collection

This study was carried out using *Tectona grandis* L.f. from a commercial plantation belonging to the Guavirá Industrial and Agroflorestal Ltda. in Nova Maringá, Mato Grosso, Brazil –13° 1′ 2′ (south latitude) and 57° 4′ 8′ (west longitude). The plantation region is located at 334 m of altitude above sea level in the Cerrado biome, with a mean annual rainfall of 1664 mm, minimum and maximum temperatures of 24 °C and 37 °C, respectively, and a tropical climate with a dry season (Aw), according to Köppen-Geiger's classification.

The materials were obtained from five distinct stands categorized by tree age. Trees with medium-sized diameters were chosen through a random sampling process. Selection criteria excluded trees with poor phytosanitary conditions and those situated on the plantation perimeters. A total of 12 trees were selected per treatment from each stand, with three treatments of seed origin and two of clonal origin, according to Table 1.

The selected trees were felled, and their stems were sectioned to collect three disks per tree at the following

Table 1 Identification of age, height, mean diameter, and origin of *Tectona grandis* trees

Treatment	Age (years)	Mean total height (m)	Mean commercial height (m)*	Mean DBHcc (cm)**	Origin
5C	5	11.40	5.00	12.82	Clonal
10S	10	17.82	9.72	21.57	Seed
10C	10	17.12	8.71	23.08	Clonal
15S	15	20.65	10.36	26.22	Seed
20S	20	20.42	8.79	26.35	Seed

*Mean commercial height = height of first fork; **DBHcc = diameter at breast height with bark (1.3 m from the soil)

positions: base (0.1 m), 2.3 m (end of the first commercial log), and top (100% commercial height) (Fig. 1). The primary Brazilian teak wood product is short logs measuring 2.20 m in length. The first log of a tree, from the base (0.1 m) to 2.3 m, represents the tree's most economically valuable part. For this reason, the sampling considered these two regions.

2.2 Morphological parameters

The base, 2.3 m, and top disks were polished using a belt grinder with 100-grit sandpaper, after which they were photographed with a digital camera. Visual color distinctions at the macroscopic level facilitated the identification of the pith, heartwood, sapwood, and bark (Fig. 1). For delimitation and quantification of each variable, we used ImageJ software (Schneider et al. 2012), utilizing a 1 cm calibration. Subsequently, we calculated the percentages of pith, sapwood, heartwood, and bark in relation to the total disk area. Additionally, we computed the percentage of each variable per tree by taking the arithmetic mean across the three disks for each tree.

The volumes of the stem with bark, without bark, and heartwood per tree were calculated using Smalian's method. It involves measuring the diameters at the ends of each log section (base – 2.3 m; 2.3 m – top). The total volume was calculated by summing the volumes of each section:

$$V_i = \frac{(g_1 + g_2)}{2} l \quad (1)$$

where V_i = volume of the i-th log section (m^3); g_1 = cross-sectional area at the base of the i-th log section (m^2); g_2 = cross-sectional area at the top of the i-th log section (m^2); l = length of the log section; and i = number of log sections ($i = 1, 2$).

2.3 X-ray densitometry

The wood density profile was determined using X-ray densitometry. The base disk of six trees per treatment was sectioned to obtain diametral samples with approximate dimensions of 2.0 cm (width), 3.0 cm (thickness), and a length equal to the diameter of each disk (Fig. 1). Subsequently, using a dual parallel circular saw, the samples were cut in the transverse direction, resulting in final dimensions of 2.0 cm in width, approximately 2.0 mm in thickness, and a length equal to the initial disk diameter. These samples were then identified and placed in a room with controlled temperature and humidity conditions (20 °C and 60% relative air humidity), where they remained until reaching equilibrium with the environment, achieving a moisture content of 12%.

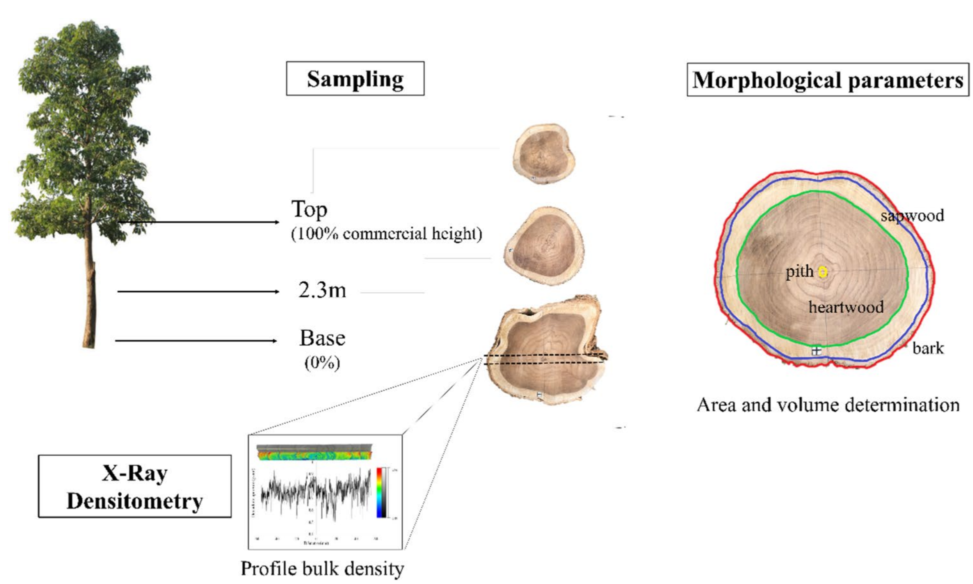

Fig. 1 Sampling methodology for disk collection and analysis of *Tectona grandis* L.f. trees at different ages

The samples were individually placed in the shielded compartment of the digital X-ray equipment Faxitron LX-60, along with a cellulose acetate calibration scale, for automatic readings (26 kV, 19 s). The analyzed images revealed the formation of well-defined growth rings. In grayscale, lighter regions indicate higher density zones due to the X-ray intensity loss in areas with higher density, while darker regions indicate lower density.

The digital images, with contrast in grayscale, were analyzed using ImageJ software (Schneider et al. 2012). A radial line was drawn, bundled with 64-bit Java, to calculate and determine the values of wood density every 50 µm. The data were transferred to a spreadsheet to create diametrical profiles of wood density. The mean values acquired from the radial wood profiles were initially averaged for each individual tree. Subsequently, the mean wood density for all individuals within each treatment was calculated, along with the minimum and maximum density values.

The radial profiles of wood density per growth ring were constructed based on the digital images. The radial profiles of density per growth ring allowed the creation of charts showing the relationship between the mean width values per growth ring (cm), wood density per growth ring ($g.cm^{-3}$), and the length of the heartwood radius (cm) of the samples. Thus, based on the generated charts, the age of transition from juvenile to mature wood was identified by the stabilization of wood density values and the reduction in growth ring width.

All images were converted to a rainbow scale in Adobe Photoshop® software. The rainbow scale has a range of colors, with blue representing lower-density areas and red indicating higher-density areas. The color palette on the rainbow scale facilitates the interpretation and localization of regions with different densities along the radial profile of the wood (Castro 2011).

2.4 Statistical analyses

For the morphological parameters (pith, heartwood, sapwood, and bark percentages; and volumes with and without bark and heartwood volume), the data were submitted to univariate analysis of variance using a completely randomized design (CRD), composed of the five treatment/age groups (5C, 10C, 10S, 15S, and 20S) and twelve repetitions (trees), totaling 60 sample units. For the mean wood density of tree bases, the CRD consisted of five treatments and six repetitions, totaling 30 sample units. If statistically significant, the means were compared using the Tukey test ($p < 0.05$). All statistical analyses were performed using RStudio software (version 2.11).

3 Results and discussion

3.1 Morphological parameters

Table 2 presents the diameters and the percentage values of heartwood, sapwood, bark, and pith along the stem of the teak trees at different ages.

The stems of all trees at all evaluated ages exhibited a conical shape from the base up to the top (Table 2). In trees aged between 5 and 15 years old, it was observed that the total diameter at the top represented approximately 50% of the diameter at the base; however, by 20 years old, this value had increased to 60%.

Regarding the heartwood diameter (Table 2), the 5-year-old trees did not exhibit heartwood at the top, up to a height of 5 m (Table 1). On average, trees of 10 years of seminal origin displayed a heartwood diameter at the top equivalent to 25% of the diameter at the base. In the same age group, the clonal material presented a heartwood diameter at the top of approximately 40% of the heartwood diameter at the base, a value similar to that found in trees of 15 years of seminal origin. This result highlights the superiority of clonal materials in terms of heartwood productivity. At 20 years old, the heartwood diameter at the top corresponded to 53% of the diameter at the base.

As expected, the diameters at the base, 2.3 m, and top of the trees increased with age. It is important to note that the difference in diameter at the base and at 2.3 m for trees aged 15 and 20 years old was approximately 2 cm. The main distinction between these two age groups lies in the total diameters and heartwood at the top, implying higher commercial value of the logs.

Table 2 presents the radial growth behavior of teak trees as a function of age, demonstrating that a larger stem diameter results in a higher proportion of heartwood and a reduced percentage of sapwood and bark. The trend of radial growth observed in this study is corroborated by studies examining teak wood at different ages (Leite et al. 2011; Zahabu et al. 2015; Benedetti 2019; Moya et al. 2020). Such behavior is associated with heartwood formation, where the radial growth of the tree leads to changes in the nature of the sapwood, which, in turn, results in heartwood formation. This process has been studied for decades and is known to be associated with parenchyma cell death, the disappearance of storage material, and an increase in extractive content (Piqueras et al. 2020). It plays a critical role in maintaining the optimal volume of sapwood, and in teak, the thickness of sapwood varies from 2 to 5 cm and remains constant at any height or tree age (Moya et al. 2014).

There is a direct relationship between the age of teak trees and heartwood formation. 5C had the lowest

Table 2 Mean values of the diameters and percentages of heartwood, sapwood, bark, and pith along the stem of *Tectona grandis* trees at different ages

Treatment	Position	Mean diameters (cm)			Mean values (%)			
		Total	Heartwood	Pith	Heartwood	Sapwood	Bark	Pith
5C	Base	14.74 (2.02)	5.95 (1.80)	0.09 (0.05)	16.35	61.81	21.34	0.49
	2.3 m	8.81 (0.95)	1.71 (1.03)	0.25 (0.28)	4.61	76.99	17.66	0.72
	Top	6.90 (0.74)	0.00 (0.00)	0.77 (0.13)	0.00	79.74	18.89	1.36
	Mean values (%)				6.98 **d** (4.07)	71.85 **a** (2.15)	17.97**a** (2.04)	0.85 **a** (0.32)
10S	Base	21.95 (3.88)	14.63 (3.07)	0.02 (0.01)	44.10	42.23	13.49	0,16
	2.3 m	15.55 (3.66)	9.87 (3,53)	0.10 (0.19)	40.80	45.97	12.80	0.42
	Top	10.69 (2.81)	3.63 (2.71)	0.17 (0.26)	12.42	72.84	14.26	0.46
	Mean values (%)				32.44 **c** (6.02)	53.68 **b** (7.54)	12.09 **bc** (3.64)	0.35 **b** (0.23)
10C	Base	22.84 (2.17)	17.24 (2.53)	0.02 (0.01)	57.00	29.51	13.28	0.20
	2.3 m	16.95 (1.86)	11.68 (2.06)	0.03 (0.01)	48.03	37.91	13.73	0.31
	Top	11.58 (2.65)	6.36 (3.21)	0.09 (0.14)	32.28	51.05	16.17	0.48
	Mean values (%)				45.77 **b** (7.01)	39.49 **c** (6.35)	13.50 **b** (2.06)	0.33 **b** (0.16)
15S	Base	28.28 (2.88)	21.42 (2.02)	0.05 (0.10)	57.69	29.73	12.26	0.30
	2.3 m	19.62 (2.39)	14.64 (2.21)	0.03 (0.01)	55.59	34.46	9.60	0.31
	Top	13.43 (1.82)	8.09 (1.90)	0.03 (0.01)	36.07	51.26	12.30	0.35
	Mean values (%)				49.78 **ab** (5.65)	38.48 **c** (10.6)	10.44 **c** (2.04)	0.32 **b** (0.31)
20S	Base	30.36 (3.22)	23.52 (2.78)	0.01 (0.01)	60.02	26.65	13.27	0.05
	2.3 m	21.51 (2.00)	16.37 (2.09)	0.02 (0.01)	57.90	31.33	10.60	0.15
	Top	17.58 (2.58)	12.62 (3.13)	0.02 (0.01)	50.87	37.85	11.03	0.24
	Mean values (%)				56.26 **a** (5.84)	31.94 **c** (4.35)	10.74 **c** (1.85)	0.15 **c** (0.12)

Mean values followed by the same letter on the column (treatments) are not significantly different ($p < 0.05$), according to the Tukey test. Values in brackets correspond to the standard deviation

heartwood percentage (6.98%). A significant increase in this percentage was observed, ranging from 32% (10S) to 45% (10C). 15S (49.78%) and 20S (56.26%) had the highest heartwood percentage values. This effect was also observed by Fernández-Sólis et al. (2018) in fast-growing plantations of different ages in Costa Rica and by Berrocal et al. (2020), who found a significant relationship between age and heartwood diameter ($R^2 = 60\%$) and heartwood percentage ($R^2 = 65\%$).

Percentages of heartwood above 55% occurred in the bases of the trees aged 10, 15, and 20 years old (Table 2). Nonetheless, the heartwood percentage was equal to or superior to 55% only for the ages of 15 and 20 years at 2.3 m. Such a finding reveals that the use of trees from the age of 15 years favors mechanical processing, generating a higher number of logs through sawmilling with the possibility of utilization, especially the lumber in central blocks, which should contain a greater heartwood proportion to be considered of greater quality and valuation. However, for premium wood markets, other quality aspects of short-rotation teak wood should be evaluated, such as log shape, aesthetic aspects—color, grain, physical properties—dimensional stability, density, mechanical properties, and natural durability (Gaitan-Alvarez et al. 2019; Moya and Tenorio 2021; Silva et al. 2023; Silva-Albuês et al. 2024).

The values found corroborate the literature on teak plantations introduced in Latin America, with mean values of 38.33% of heartwood for six-year-old clonal material found by Lemos et al. (2019), whereas Blanco-Flórez et al. (2014) reported heartwood values of 51.44% for ten-year-old trees of seed origin. Silva-Albuês et al. (2024) observed 46.16% heartwood in 15-year-old clonal teak, and Arce and Moya (2015) reported a heartwood percentage between 49.76% and 60.02% when analyzing the properties of 15-year-old clones from a teak plantation in Costa Rica.

According to Flórez (2012), heartwood percentages close to 70% suggest higher commercial values of wood, which are reached only in woods aged 50 years or older in regions where teak is native. In this study, the 20-year-old wood presented a mean of 56.26% heartwood (Table 2) and a heartwood percentage above 50% along the stem (Table 1), revealing the possibility of greater utilization of logs, thus representing a satisfactory result for a material derived from a commercial plantation in Brazil. Yang et al. (2020) found similar values when studying heartwood proportions varying between 51 and 60% for a 31-year-old seed plantation in China, thus corroborating that forest plantations containing the material evaluated herein provide the market with a material presenting similar heartwood proportions in a lower final harvesting age.

The evaluated trees presented a lower sapwood proportion as age advanced; therefore, the 5C treatment was significantly different ($p < 0.05$) from the other treatments, with a proportion above 70% (Table 2). The 5-year-old teak wood is in the early heartwood formation process, that is, it is still mostly composed of sapwood. Lemos et al. (2019) found similar proportions when studying 6-year-old teak wood of seed origin, with 76.91% sapwood.

However, even though sapwood is not considered the principal material of teak wood (Flórez 2012), in the Brazilian domestic market, sapwood is used in products of lower added value. These include props for civil construction, piles, fence posts, edged glued panels (EGP), small furniture, kitchenware, and firewood (Paes et al. 2015).

Regarding the bark proportion, 5C presented higher percentages when compared to the other ages evaluated, with a value above 15% (Table 2), a behavior related to the growth stages of the trees. The larger the stem diameters, the lower the bark percentage due to the volumetric increase. Therefore, lower proportions of bark are found in older teak trees, which exhibit larger stem diameters (Berrocal et al. 2020; Vendruscolo et al. 2019).

All treatments evaluated showed a trend of lower bark percentage as the age of the teak wood advanced. Leite et al. (2011) also observed such a trend when evaluating 3- and 12-year-old teak trees, with a bark percentage of 35% and 10%, respectively. Additionally, they noted that the mean value decreased exponentially with the increase in DBH.

Since bark is regarded as a product of secondary importance in teak plantations, the forest sector considers it important to be estimated only for discard (Vendruscolo et al. 2019). However, bark can also be considered an alternative source of income for industries since it is rich in extractives and lignin. Extractives can be applied in a wide range of bioproducts, and lignin can be used to produce polymers, resins, and bonds (Lourenço et al. 2015).

The 5C and 20S treatments presented significant differences ($p < 0.05$), and at 5 years old, the pith proportion was higher than that in the other treatments. Such a result occurs due to the lower stem diameter of the 5-year-old trees compared with the more advanced ages; therefore, the older the tree is, the larger the stem diameter and hence the lower the pith percentage. However, the area occupied by the pith corresponds to a lower percentage than 1% in the evaluated treatments (Table 2), thus not affecting the utilization of teak wood. Furthermore, the pith diameter (Table 2) was also greater for the 5-year-old trees. The same trend of decreasing diameter and pith percentage with the age of teak trees was found by Berrocal et al. (2020). This occurs because growth stress in the tree increases as the diameter grows, producing a compressive force that can reduce the pith diameter as the tree ages (Archer 1986).

Table 3 presents the mean volume values of the stem with bark (total volume), stem without bark, and heartwood at the different ages evaluated. All variables determined showed significant differences ($p < 0.05$) between ages.

The heartwood volume values (Table 3) reinforce the potential for heartwood production in fast-growing commercial plantations in Brazil. They indicate that the wood from the evaluated commercial plantation has high acceptance in the global market. It is worth highlighting that the primary teak products are unprocessed logs with a length of 2.2 m and rough-sawn timber, which comes in prismatic blocks measuring either 10 × 10 cm or 15 × 15 cm in width. Therefore, higher heartwood volumes result in blocks with less sapwood, hence a product of greater added value. Therefore, quantifying the volumes of heartwood and sapwood is important for the wood to be valued in the commercial market, where higher heartwood contents in mature trees result in higher natural durability (Oliveira et al. 2019).

The assessment of volumes of the stem with and without bark (Table 3) showed that the 15S and 20S treatments were statistically equal ($p < 0.05$). When considering the quality of the product concerning the amount of heartwood, the present study also demonstrates that the use of 15- or 20-year-old trees would provide the market with a higher-quality wood. It is worth noting that the volume of heartwood in 20S was, on average, 20% (0.038 m^3) higher than that in 15S.

The heartwood proportion in the 10-year-old trees showed a significant difference, with 45.77% and 32.44% for the clonal origin and seed origin materials, respectively (Table 2). Lemos et al. (2019) also reported such behavior when comparing teak wood of seed and clonal origins. These authors observed that the 6-year-old clones had a higher heartwood proportion (15.24%) than the seed material. Additionally, when considering the volumes of heartwood (Table 3), although the 10S and 10C treatments were

Table 3 Mean values of bark, sapwood, heartwood, pith, and volumes of stem with bark, without bark, and volume of heartwood (m^3) of trees of *Tectona grandis* at different ages

Treatment	Mean volume per tree (m^3)		
	Total	Without bark	Heartwood
5C	0.039 **c** $^{(0.01)}$	0.032 **c** $^{(0.009)}$	0.004 **c** $^{(0.002)}$
10S	0.172 **b** $^{(0.05)}$	0.150 **b** $^{(0.05)}$	0.065 **b** $^{(0.02)}$
10C	0.178 **b** $^{(0.03)}$	0.153 **b** $^{(0.03)}$	0.086 **b** $^{(0.03)}$
15S	0.287 **a** $^{(0.06)}$	0.256 **a** $^{(0.05)}$	0.150 **a** $^{(0.03)}$
20S	0.325 **a** $^{(0.09)}$	0.288 **a** $^{(0.08)}$	0.188 **a** $^{(0.06)}$

Means followed by the same letter on the columns are not significantly different ($p < 0.05$), according to the Tukey test. Values in brackets correspond to the standard deviation statistically equal ($p < 0.05$), the volume of heartwood per tree was 25% (0.021 m^3) greater in 10C than 10S.

In addition, the 10C treatment was statistically equal to the 15S treatment concerning the percentages of heartwood (Table 2). This result indicates that the use of selected genetic material might reduce the final harvesting age regarding heartwood proportion. In addition, for a commercial teak plantation primarily focused on producing logs or blocks, plantation uniformity is a crucial requirement. They provide the market with products of greater similarities. In this context, the 5C and 10C treatments presented a standard deviation inferior to that of the seed materials (Table 3). It is worth highlighting that age influences volume; therefore, the heartwood volume in the 15S treatment was significantly different from that in the 10C treatment, corroborating that regardless of the clonal material used, age is a decisive factor in the formation of heartwood in the stem.

3.2 Wood density by X-ray densitometry

Table 4 shows the mean, minimum, and maximum values of wood density (U%~12%) determined by X-ray densitometry for the base of teak trees from fast-growing plantations aged 5 to 20 years. Figure 2 introduces the densitometric profile, which represents the mean of the six samples analyzed per treatment. It is important to note that the assessment of wood density using the microdensity technique occurs every 50 µm, resulting in a wide range of values (Fig. 2). This variation is influenced by the anatomical components of the wood. When a specific point in the radial profile corresponds to the fiber wall, the values are high, as demonstrated in the maximum values presented in Table 4. However, when parenchyma cells, vessel lumens, pith, or even microcracks are evaluated, the density is lower (Table 4). As an example, the minimum density of 0.03 found in treatment 20C corresponds to the pith area, observed in the first few millimeters of the radial profile (Fig. 3e).

The 5C treatment presented the highest wood density value (Table 4), statistically differing ($p < 0.05$) from all other ages, whose mean values varied between 0.60 and 0.66 g.cm^{-3}. The wood of all treatments was classified as moderate density (500–750 kg/m^3), according to Csanády et al. (2015). The highest mean wood density was observed in the 5-year-old wood, a stage at which teak wood consists entirely of juvenile wood. It is interesting to note in Figs. 2, 3, and 4 that the wood density in the first five years of the 10C, 10S, 15S and 20S treatments did not reach densities as high as the 5C treatment. This fact could indicate the superiority of the clonal material evaluated. Studies on the quality of teak wood of trees at different ages have indicated that juvenile wood, in contrast to many species from a temperate climate, is not inferior to mature wood in terms of density and mechanical resistance (Bhat and Florence 2003; Lopes 2012).

Table 4 Mean, maximum, and minimum wood density by X-ray densitometry for *Tectona grandis* at different ages

Treatment	Mean	Minimum	Maximum
5C	0.74 **a** (0.05)	0.31	1.00
10S	0.60 **b** (0.05)	0.22	0.95
10C	0.61 **b** (0.09)	0.12	0.96
15S	0.63 **b** (0.09)	0.17	0.98
20S	0.66 **b** (0.10)	0.03	0.99

Means followed by the same letter are not significantly different ($p < 0.05$), according to the Tukey test. Values in brackets correspond to the standard deviation

When comparing ages from 10 to 20 years old, a trend of increasing mean wood density as the age of the trees advanced (Table 4) was observed, with 0.66 g.cm^{-3} in the 20-year-old wood. The mean values of wood density of *Tectona grandis* found herein are close to those observed in studies that used the technique of X-ray densitometry. Chagas et al. (2014) studied 4-, 6-, and 12-year-old teak wood and determined mean density values of 0.53, 0.51, and 0.53 g.cm^{-3}, respectively. In turn, Amodei et al. (2021) analyzed 11-year-old teak wood and obtained a mean value of 0.60 g.cm^{-3}, whereas González (2013) examined the growth rings of 36-year-old teak and found a mean wood density of 0.64 g.cm^{-3}.

Figure 3 shows the radial density profile with the identification of annual growth rings and heartwood radius. Figure 4 illustrates the relationship between the mean width values per growth ring and wood density per growth ring.

T. grandis displays semi-ring-porous wood with well-differentiated annual rings, primarily due to pore size (Fig. 3f). It enables the distinction of annual rings in teak through X-ray densitometry (Nocetti et al. 2011; Gaitan-Alvarez et al. 2019). However, it is not possible to determine the sapwood-heartwood boundary using this technique (Gaitan-Alvarez et al. 2019), as observed when correlating the red arrows in Figs. 3 and 4, which indicate the heartwood radius, to density profiles.

All samples analyzed at 5 years old had a slightly high wood density along the radial profile (Figs. 2a, 3a), 0.75 (ring 1) to 0.72 (ring 5). In addition, X-ray densitometry and both the gray and rainbow scales revealed that the yearly limits of the growth rings were marked with greater sharpness. The growth rings present a constant width, which is correlated with the small variation amplitude of the wood density values (Fig. 4a). The 5-year-old wood is characterized by the presence of juvenile wood, composing the whole wood, even in the region containing heartwood within a 3.45 cm radius (Figs. 3a, 4a).

Nonetheless, Gaitan-Alvarez et al. (2019) did not find yearly sharpness of the growth rings observed herein when

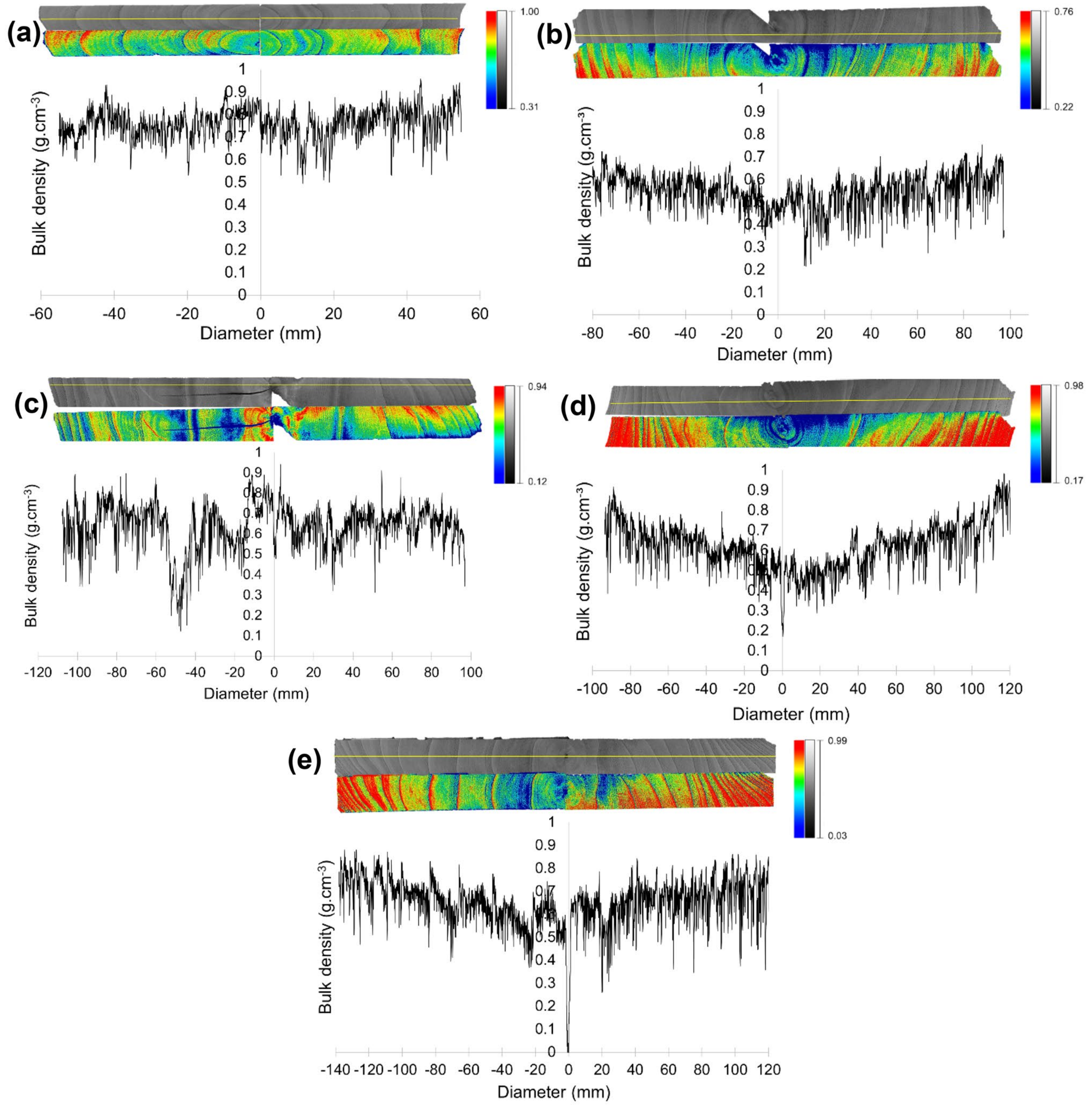

Fig. 2 Diametral wood density profile (g.cm^{-3}) of *Tectona grandis* tree bases from Brazilian plantations: **a** 5C—clonal origin, five-year-old; **b** 10S—seed origin, ten-year-old; **c** 10C—clonal origin, ten-year-old; **d** 15S—seed origin, fifteen-year-old; **e** 20S—seed origin, twenty-year-old

assessing only the density profiles of *T. grandis* wood by X-ray densitometry. The authors found no sharpness in the delimitation of growth rings over the first eight years of the tree, which they attributed to the higher growth rates reached by teak wood during its early years in commercial plantations and the presence of false rings; however, neither gray nor rainbow scale was applied to demarcate the rings, thus generating difficulty in delimitating the growth rings.

Despite its limitations, such as low-class diameter and high index of juvenile wood, five-year-old teak trees can be used in round timber preservation and production of pencils and kitchenware; however, some challenges must be overcome, such as the presence of warping, surface cracking, cracks, and the low biological resistance of sapwood to the attack of xylophagous organisms (Paes et al. 2015).

The density profile for 10-year-old trees revealed that the material in both the gray and rainbow scales (Figs. 2b, c, 3b,

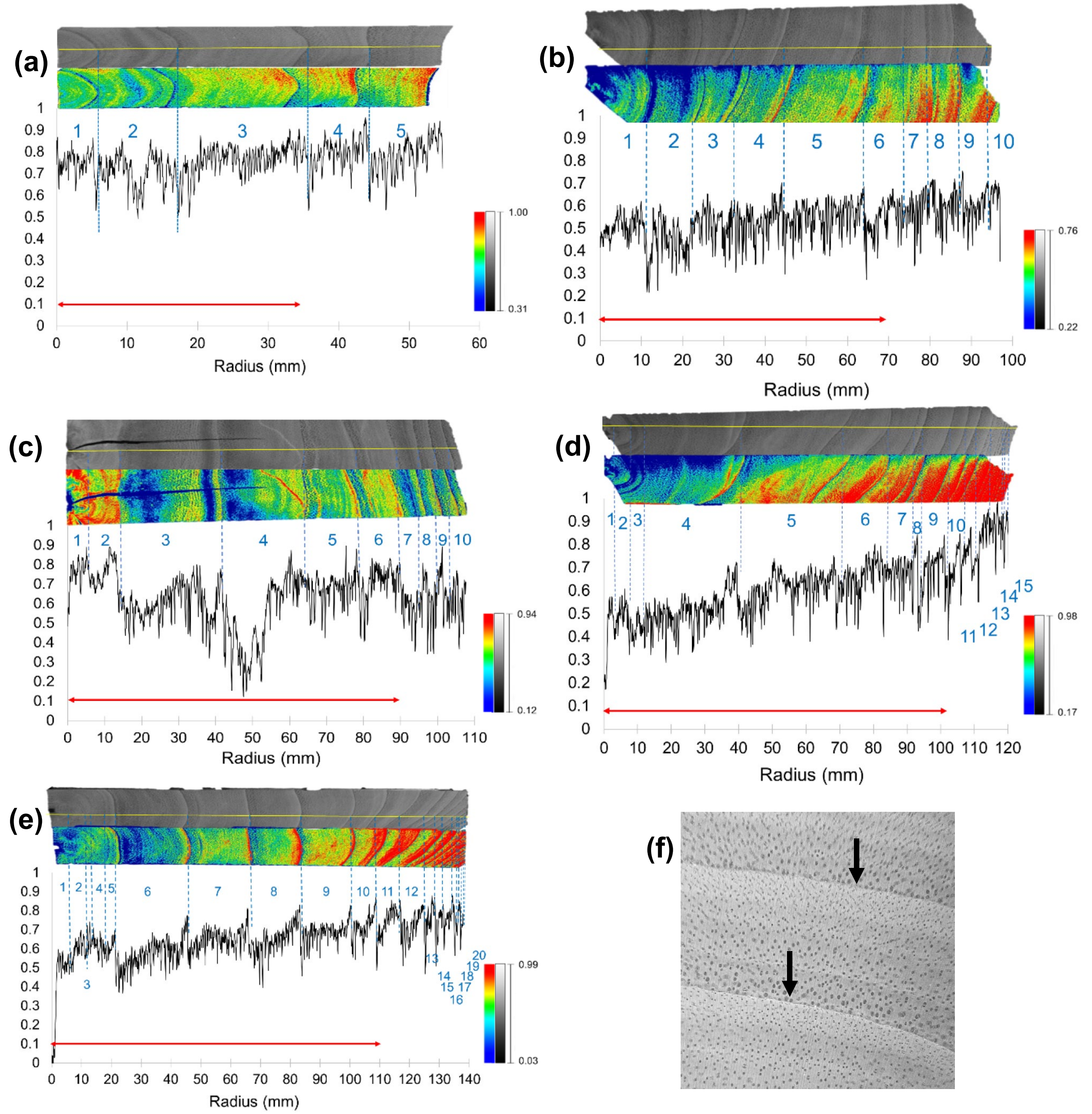

Fig. 3 Wood density profile for the annual growth rings (g.cm^{-3}) of *Tectona grandis* tree bases from Brazilian plantations: **a** 5C—clonal origin, five-year-old; **b** 10S—seed origin, ten-year-old; **c** 10C—clonal origin, ten-year-old; **d** 15S—seed origin, fifteen-year-old; **e** 20S—seed origin, twenty-year-old. **f** Detail of the annual ring boundary in the X-ray densitometry image. The red arrows represent the heartwood radius (**a**–**e**)

and c) had the presence of cracks in the pith region. These zones have valleys, which are characterized by the accumulation of parenchyma. The transition from juvenile to mature wood through the thickness of the rings was observed from seven years old for the seed material (Fig. 4b) and from eight years old for the clonal material (Fig. 4c). The heartwood present in the ten-year-old basal samples is composed of both juvenile wood and transition from juvenile to mature wood. Such a finding correlates to the density values per growth ring for the ten-year-old trees (Fig. 4b and c), where greater density values are observed in the edges of the disk, whereas lower values occur close to the pith. Therefore, the

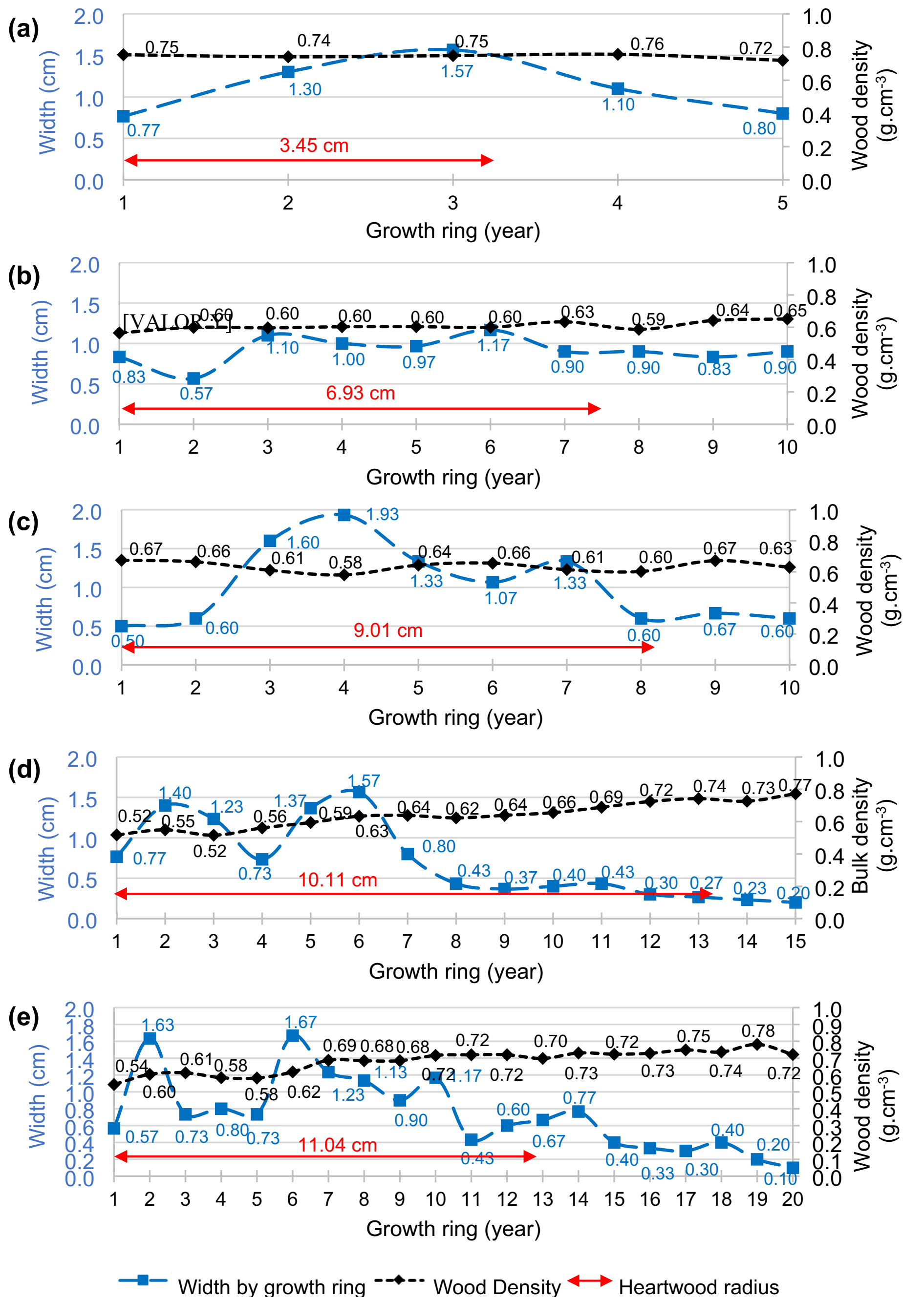

Fig. 4 Relationship between mean width (cm) and wood density (g.cm^{-3}) by growth ring and heartwood radius of the *Tectona grandis* tree base: **a** 5C—clonal origin, five-year-old; **b** 10S—seed origin, ten-year-old; **c** 10C—clonal origin, ten-year-old; **d** 15S—seed origin, fifteen-year-old; **e** 20S—seed origin, twenty-year-old

ten-year-old samples show that the wood of the teak trees is not uniform in the pith-bark direction, and their initial growth rings have lower wood density, whereas the final growth rings present higher density due to the changes in anatomical structure.

In teak wood, the earlywood of an annual ring consists of a narrow band of numerous and large lumen vessels, which is why tree-ring density values are low at the beginning of an annual ring (Gaitan-Alvarez et al. 2019). The vessel diameter gradually decreases at the end of the annual ring, resulting in a gradual increase in wood density (Nocetti et al. 2011). Moreover, the wider the growth ring is, the greater the proportion of earlywood. Furthermore, the vessel frequency per mm^2 decreases from pith to bark as the vessel diameter increases (Moya et al. 2009; Rodríguez-Anda et al. 2018). Bhat et al. (2001) suggest that cambium activity may be higher in the early stages of plant development, leading to the formation of more vessels, which can directly influence wood density. Rahman et al. (2007) mention that the number of vessels, along with the proportion of medullary rays, has a significant relationship with wood density. As fiber length increases, the thickness of the cell wall also tends to increase from the pith to the bark (Rodríguez-Anda et al. 2018).

Our study verified that the older the age, the easier the definition of the annual growth rings. The density profile exhibited pronounced sharpness between the boundary growth rings from approximately seven years old (Fig. 3b–e). This effect is observable through the application of X-ray densitometry, as described by Castro (2011). It enables the precise determination of the growth ring boundaries and the identification of false rings. These false rings are formed in tree wood in response to the environmental fluctuations experienced by the trees. Gaitan-Alvarez et al. (2019) applied X-ray densitometry to teak wood and corroborated that mature trees of fast-growing plantations present better-defined yearly rings than juvenile trees. Nonetheless, these authors considered that identifying the yearly rings might be difficult in older trees due to the climate variations to which the tree is subjected throughout its growth.

The densitometric profile of the 15- and 20-year-old trees also revealed a trend of increasing wood density along the radial profile. The wood in the inner region displayed a lower density value when compared to the outer region, as well as narrower growth rings in proximity to the bark (Fig. 4d, e). All of these factors indicate the presence of mature wood starting at 11 years old for 15S and 20S. Anatomically, the presence of juvenile and mature wood is detected by identifying the cell dimensions characterizing each zone, where fibers with higher wall thickness and lower microfibrillar angle generate peaks of wood density in the profile, indicating the presence of mature wood; in turn, the occurrence of wider diameters generates a lower density value, indicating the presence of juvenile wood (Bhat and Florence 2003; Chagas et al. 2014).

Therefore, the lower the variety of peaks and valleys in a single line, the more homogenous the wood density. Therefore, woods with uniform density along the stem have more possibilities of utilization because they are less prone to defects while in use. The basal profile from the 15-year-old trees indicates that the heartwood primarily comprises juvenile wood, with mature wood accounting for approximately 2.02% of the heartwood composition (Figs. 3d, 4d). On the other hand, the heartwood of the 20-year-old trees is predominantly composed of juvenile wood, with mature wood constituting only 0.18% of the heartwood composition (Figs. 3e, 4e).

It is important to emphasize that the presence of heartwood with high proportions of mature wood is highly prized in the market, as it offers a product with characteristics closely resembling native teak quality. Consequently, the heartwood radius values obtained in this study (Figs. 4d, e) indicate that only the 15- and 20-year-old trees possess heartwood containing mature wood. To produce logs with a high proportion of heartwood containing mature wood, the assessed commercial fast-growing plantations should have an extended final rotation age. This could result in a product with superior properties for various high-value applications.

4 Conclusion

Teak trees in Brazilian fast-growing plantations already exhibit heartwood in the base region at five years old. The proportion of heartwood increases with tree age and decreases with tree height. On the other hand, the proportion of sapwood and bark decreases as the trees age.

Teak wood from 5-year-old clonal fast-growing plantations had a higher mean wood density in relation to the other ages.

There was a trend of increasing wood density as the trees aged from ten years. The diameter profiles obtained by X-ray densitometry indicated a higher wood density in the pith-to-bark direction, regardless of the age evaluated, with variation within the growth ring. This technique allowed for a precise delimitation of annual growth rings, but with increasing age, it became easier.

Until the age of 10 years, teak trees in fast-growing plantations exhibit only juvenile wood. From 15 years old onwards, the trees already present mature wood, including in the heartwood, with the transition occurring after the 11th year. Therefore, to promote the development of teak mature wood, it is recommended to increase the final harvesting age in Brazilian teak commercial plantations.

Acknowledgements We thank the Wood Technology Laboratory from the Federal University of Mato Grosso and the Wood Properties Laboratory of the Federal University of Viçosa for all team contributions. We also thank Guavirá Industrial and Agroflorestal Ltda. for the supply of materials necessary for the realization of this work. Finally, we are grateful for the financial support of the Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil).

Author contributions Conceptualization: Curvo, K R; Oliveira, A C; Pereira, B L C. Methodology: Curvo, K R; Silva, G A O; Castro, V R; Gava, F H. Formal analysis and investigation: Curvo, K R; Oliveira, A C; Pereira, B.L. C; Castro, V R. Writing—original draft preparation: Curvo, K R. Writing—review and editing: Pereira, B.L. C; Aylson Costa Oliveira; Supervision: Oliveira, A C; Pereira, B.L. C; Castro, V R. The manuscript is part of the Master's dissertation of the first author. All the authors have read and approved the final manuscript.

Funding Not applicable.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest All authors declare that they have no conflicts of interest.

References

Amodei JB, Latorraca JV de F, Santos GCV dos, Martins BC (2021) Wood quality of young teak in different planting spaces. Floresta e Ambiente https://doi.org/10.1590/2179-8087-floram-2021-0026

Arce N, Moya R (2015) Wood characterization of adult clones of *Tectona grandis* growing in Costa Rica. Cerne 21:353–362. https://doi.org/10.1590/01047760201521031751

Archer RR (1986) Growth stresses and strains in trees. Springer, New York

Barrantes-Madrigal K, Murillo-Cruz R, Ávila-Arias C, et al (2021) Tabla de volumen comercial para teca clonal en diferentes índices de sitio en la Zona Norte de Costa Rica. (Table of commercial volume for clonal teak at different site indices in Northern Costa Rica). Revista de Ciencias Ambientales 55:211–229. https://doi.org/10.15359/rca.55-1.10

Benedetti V (2019) Characterization of teak wood planted in different ages and regions for floor production. Dissertation, University of São Paulo (In Portuguese)

Berrocal A, Gaitan-Alvarez J, Moya R et al (2020) Development of heartwood, sapwood, bark, pith and specific gravity of teak (*Tectona grandis*) in fast-growing plantations in Costa Rica. J For Res (Harbin) 31:667–676. https://doi.org/10.1007/s11676-018-0849-5

Bhat KM, Florence EJM (2003) Natural decay resistance of juvenile teak wood grown in high input plantations. Holzforschung 57:453–455. https://doi.org/10.1515/HF.2003.067

Bhat KM, Priya PB, Rugmini P (2001) Characterization of juvenile wood in teak. Wood Sci Technol 34:517–532. https://doi.org/10.1007/s002260000067

Blanco-Flórez J, Fernando-Trugilho P, Tarcisio-Lima J, et al (2014) Caracterización de la madera joven de *Tectona grandis* L. f. plantada en Brasil. (Characterisation of juvenile wood of Tectona grandis L. f. planted in Brazil). Madera y Bosques 20:11–20. https://doi.org/10.21829/myb.2014.201172

Blanco-Flórez J, Silva JRM da, Braga PP de C, et al (2015) Simulation in service of young teak wood floors. Matéria (Rio de Janeiro) 20:1048–1060. https://doi.org/10.1590/S1517-707620150004.0107 (In Portuguese)

Canal WD, Carvalho AMML, Carneiro A et al (2020) Effect of age on heartwood/sapwood relationship extractive content, and permeability of teak wood. Floresta 50:1698–1706. https://doi.org/10.5380/rf.v50i4.59077

Castro VR de (2011) Application of nondestructive methods to evaluate physical properties of the wood of trees of *Pinus caribaea* var. *hondurensis* Barr. et Golf. and *Tectona grandis* (L.f.). Thesis, University of São Paulo (In Portuguese)

Chagas SF, Evangelista WV, De Castro Silva J, et al (2014) Properties of teakwood of different ages coming from thinning. Revista Ciência da Madeira (Brazil J Wood Sci). 5:10. 10-12953/12177-16830/v12905n12902a12908 (In Portuguese)

Csanády E, Magoss E, Tolvaj L (2015) Quality of machined wood surfaces. Springer, Switzerland

Damayanti R, Ilic J, Ozarska B et al (2019) Effect of clone and sites for wood properties of fast grown teak and determination of the best clone for next cultivation in teak plantation industries. IOP Conf Ser Earth Environ Sci. https://doi.org/10.1088/1755-1315/359/1/012002

Darmawan W, Nandika D, Sari RK et al (2015) Juvenile and mature wood characteristics of short and long rotation teak in Java. IAWA J 36:428–442. https://doi.org/10.1163/22941932-20150112

de Oliveira MB, da Silva JRM, Hein PRG, Lima JT (2019) Establishment of quality classes for hardwood floorings by simulated use. Cerne 25:105–109. https://doi.org/10.1590/01047760201925012618

Delucis RA, Gatto DA, Stangerlin DM et al (2014) Delimitation methods of juvenile and mature woods of three hardwoods and biometric properties of their fibers. Revista Árvore 38:943–950. https://doi.org/10.1590/S0100-67622014000500019(In Portuguese)

Dias ACC, Marchesan R, Almeida VC, et al (2018) Relationship between basic density and shrinkage in teca wood. Revista Ciência da Madeira (Brazil J Wood Sci). 9:37–44. https://doi.org/10.12953/2177-6830/rcm.v9n1p37-44 (In Portuguese)

Fernández-Sólis, D., Berrocal A, Moya R. (2018). Heartwood formation and prediction of heartwood parameters in *Tectona grandis* L.f. trees growing in forest plantations in Costa Rica. Bois & Forets Des Tropiques 335:25–37. https://doi.org/10.19182/bft2018.335.a31499

Flórez JB (2012) Technological characterization of young teak wood. Dissertation, University of Lavras (In Portuguese)

Gaitan-Alvarez J, Moya R, Berrocal A (2019) The use of X-ray densitometry to evaluate the wood density profile of *Tectona grandis* trees growing in fast-growth plantations. Dendrochronologia (verona) 55:71–79. https://doi.org/10.1016/j.dendro.2019.04.004

Gava FH, Drescher R, Caldeira SF, et al (2021) Volume, increment and growth in clonal and seminal canopy damages stands of Teak. Revista Forestal Mesoamericana Kurú 18:79–86. https://doi.org/10.18845/rfmk.v19i43.5812 (In Portuguese)

Giustina L della, Rossi AAB, Vieira FS, et al (2017) Genetic variability of teak (*Tectona grandis* Linn. F.) based on ISSR molecular markers and morphological characterization. Ciência Florestal 27:1311–1324. https://doi.org/10.5902/1980509829894 (In Portuguese)

González ADV (2013) Dendrochronology of *Tectona grandis* L. and *Pinus caribaea* var. *hondurensis* Barr. et Golf. trees from plantation of Mata da Pedreira, Campus ESALQ-USP, Piracicaba, SP. Dissertation, University of São Paulo (In Portuguese)

Hao J, Jia H, Yanget B et al (2022) Growth process and heartwood formation for planted teak (*Tectona grandis*) in South China. Austral J For Sci 2:97–116

Leite HG, de Oliveira-Neto RR, Monte MA et al (2011) Taper models of heartwood of *Tectona grandis* Lf. Scientia Forestalis 39:053–059 ((In Portuguese))

Lemos JADS, Oliveira AC, Pereira BLC, et al (2019) Influence of the propagation method on the production and quality of *Tectona grandis* wood. Adv For Sci 6:761. https://doi.org/10.34062/afs.v6i3.8183 (In Portuguese)

Lima IL, Ranzini M, Longui EL, et al. (2021). Wood characterization of *Tectona grandis* L. F. cultivated in Brazil: a review of the last 30 years. Res Soc Develop 10:1–14 https://doi.org/10.33448/rsd-v10i14.21549

Lopes J de O (2012) Uniformity and stability of color of the heat-treated *Tectona grandis* L. f. wood. Dissertation, Universidade Federal Rural do Rio de Janeiro (In Portuguese)

Lopes J de O, Garcia RA, Nascimento AM do, Latorraca JV de F (2014) Color uniformization of the young teak wood by heat treatment. Revista Árvore 38:561–568. https://doi.org/10.1590/S0100-67622014000300019 (In Portuguese)

Lourenço A, Neiva DM, Gominho J et al (2015) Characterization of lignin in heartwood, sapwood and bark from *Tectona grandis* using Py–GC–MS/FID. Wood Sci Technol 49:159–175. https://doi.org/10.1007/s00226-014-0684-6

Miranda DLC, Loch VM, Silva F, el at (2017) Heartwood percentage, sapwood and bark five timber species of the amazon. Nativa 5: 619-627. https://doi.org/10.5935/2318-7670.v05nespa24 (In Portuguese)

Moya R, Berrocal A, Serrano JR, Tomazello FM (2009) Variación radial de la anatomía, densidad y durabilidad de la madera de teca (*Tectona grandis*) procedente de dos calidades de sitio y dos regiones climáticas de Costa Rica. (Radial variation of anatomical features, wood density and decay resistance in teak ("Tectona

grandis") from two qualities of growing sites and two climatic regions of Costa Rica). Investigación Agraria: Sistemas y Recursos Forestales 18:119–131
Moya R, Bond B, Quasada H (2014) A review of heartwood properties of *Tectona grandis* trees from fast-growth plantations. Wood Sci Technol 2:411–433. https://doi.org/10.1007/s00226-014-0618-3
Moya R, Tenorio C (2021) Wood properties and their variations in teak In: Ramasamy Y, Galeando E (Ed). The Teak Genome, Compendium of Plant Genome. Springer, Cham. pp 208
Moya R, Gaitán-Álvarez J, Ortiz-Malavassi E, et al (2020) Equations for predicting heartwood merchantable volume and tradable sawlog in *Tectona grandis*. J Trop For Sci 32: 379–390. https://doi.org/10.26525/jtfs2020.32.4.379
Nocetti M, Rozenberg P, Chaix G, Macchioni N (2011) Provenance effect on the ring structure of teak (*Tectona grandis* Lf) wood by X-ray microdensitometry. Ann For Sci 68:1375–1383. https://doi.org/10.1007/s13595-011-0145-4
Paes JB, Santos LL, Silva LF et al (2015) Technological characterization of juvenile wood teak (*Tectona grandis*) to production of furnitures. Revista Brasileira De Ciências Agrárias Brazil J Agricult Sci 10:437–442. https://doi.org/10.5039/agraria.v10i3a3906. (In Portuguese)
Piqueras S, Füchtner S, Oliveira RR, Gómez-Sánchez AG, Jelavić S, Keplinger K, Juan A, Thygesen LG (2020) Understanding the formation of heartwood in Larch using synchrotron infrared imaging combined with multivariate analysis and atomic force microscope infrared spectroscopy. Front Plant Sci 10:1–15. https://doi.org/10.3389/fpls.2019.01701
Rahman MM, Fujiwara S, Kanagawa Y (2007) Variations in volume and dimensions of rays and their effect on wood properties of teak. Wood Fiber Sci 37:497–504. Retrieved from https://wfs.swst.org/index. php/wfs/article/view/1598/1598
Reategui-Betancourt J-L, Arriel DA-A, Caldeira S-F, et al (2020) Morphological descriptors for the characterization of teak clones (*Tectona grandis* L.f.) in plantations. For Syst 29:eRC02. https://doi.org/10.5424/fs/2020292-15634
Richter HG, Leithoff H, Sonntag U (2003) Characterisation and extension of juvenile wood in plantation grown teak (*Tectona grandis* L.f.) from Ghana. In: Quality timber products of teak from sustainable forest management. Proceedings of the international conference on quality timber products of teak from sustainable forest management. Peechi, India, pp 67–70
Rios PD, Vieira HC, Pereira GF, et al (2018) Radial and longitudinal variation of basic density of *Pinus patula* wood. Pesquisa Florestal Brasileira 38. https://doi.org/10.4336/2018.pfb.38e201501016 (In Portuguese)
Rocha HF, Leonardo FVS, Oliveira AC (2015) Commercial plantations of *Tectona grandis* L.f. on Brazil. Multitemas 20:9–28. https://doi.org/10.20435/multi.v0i48.137 (In Potuguese)
Rodriguez-anda R, Fuentes-Talavera FJ, Silva-Guzman JA et al (2018) Relationship of the cellular structure of teak wood (*Tectona grandis* L. f.) with different ages and growth sites. Revista Chapingo Serie Ciencias Forestales Y Del Ambiente 24:101–114. https://doi.org/10.5154/r.rchscfa.2017.07.050
Rosa T de F de D, Scaramuz WLMP, Feitosa IP, Abreu FFM de (2017) Litter production and decomposition in teak populations in Mato Grosso state, Brazil. Ciência Florestal 27:1117–1127. https://doi.org/10.5902/1980509830288 (In Potuguese)
Schneider CA, Rasband WS, Eliceiri KW (2012). NIH Image to ImageJ: 25 years of image analysis. Nat Methods https://doi.org/10.1038/nmeth.2089
Silva GAO, Curvo KR, Oliveira AC, et al. (2023) Effect of age on heartwood proportion, color, chemical composition, and biological resistance of teakwood. Bioresources 18: 4116–4131. https://doi.org/10.15376/biores.18.4116-4131
Silva-Albuês TA, Corradi-Pereira BL, Carvalho-Guimarães A, et al (2024). Quality of *Tectona grandis* for sawn wood production. Maderas-Cienc Tecnol. https://doi.org/10.22320/s0718221x/2024.06
Takizawa FH, Medeiros RA, Leite HG, Borém A (2022) Teca: do plantio a colheita (Teak: from planting to harvesting). UFV, Viçosa. (In Portuguese)
Vendruscolo DGS, Drescher R, Carvalho S de PC, et al (2019) Modeling the thickness and percentage of bark on trees of *Tectona grandis* L.f. Scientia Forestalis https://doi.org/10.18671/scifor.v47n121.14
Yang B, Jia H, Zhao Z et al (2020) Horizontal and vertical distributions of heartwood for teak plantation. Forests 11:225. https://doi.org/10.3390/f11020225
Zahabu E, Raphael T, Chamshama SAO et al (2015) Effect of spacing regimes on growth, yield, and wood properties of *Tectona grandis* at longuza forest plantation, Tanzania. Int J Forest Res. https://doi.org/10.1155/2015/469760