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# Wood Quality of Young *Tectona grandis* L. f. Trees and Its Relationship with Genetic Material and Planting Site in Mato Grosso, Brazil

**Leandro Vinicius Carbonato de Souza [1], Jackeline Eliada Cichoski da Silva [1], Tielis Lucas Bianchini Azevedo [1], Adriano Reis Prazeres Mascarenhas [2], Luis Alberto Ugalde Arias [3], Bárbara Luísa Corradi Pereira [1] and Aylson Costa Oliveira [1,*]**

1 Graduate Program in Forest and Environmental Sciences, Forest Engineering Faculty, Federal University of Mato Grosso (UFMT), Cuiabá 78060-040, MT, Brazil; leandrocarbonato@hotmail.com (L.V.C.d.S.); jackecichoski@gmail.com (J.E.C.d.S.); tielislucas@hotmail.com (T.L.B.A.); barbara.pereira@ufmt.br (B.L.C.P.)

2 Department of Forestry Engineering, Federal University of Rondônia (UNIR), Rolim de Moura 76801-059, RO, Brazil; adriano.mascarenhas@unir.br

3 Independent Researcher, San José 30303, SJ, Costa Rica; laugalde@gmail.com

* Correspondence: aylsoncosta@gmail.com

**Abstract:** *Tectona grandis* L. f. (teak) is highly valued in the international market, but its volume and properties vary depending on its genetic material and planting site. Evaluating these factors is crucial for promoting new plantations. Therefore, this study aimed to assess the impact of genetic material (clones TG1 and TG3 and seminal material) and planting site (Nova Maringá and Água Boa, Mato Grosso, Brazil) on morphological parameters (heartwood, sapwood, bark, pith proportions, and pith eccentricity), physical properties (shrinkage and air-dry density), and mechanical properties (static bending strength—fm, compressive strength—fc0, Janka hardness—fH90, and shear strength—fv0). For this purpose, we sampled five trees aged 13 years per genetic material from commercial plantations. In Nova Maringá, trees exhibited, on average, 56.07% heartwood, while in Água Boa, this value was less than 50%. Seminal material showed the lowest percentage of heartwood (49.2%). The pith percentage was significantly greater in Água Boa than in Nova Maringá, regardless of the genetic material. We observed the highest standard deviation (5.61) in pith eccentricity for the seminal material. Both the planting site and genetic material influenced the air-dry density (~12% moisture content), which ranged from 0.535 to 0.618 g·cm$^{-3}$. Trees grown in Nova Maringá produced wood with higher dimensional stability than those from Água Boa, exhibiting a 14% lower radial shrinkage and a 6% lower volumetric variation. In Nova Maringá, the wood from the seminal material exhibited greater resistance. On the other hand, in Água Boa, that material showed lower resistance (fv0, fm, and fc0), or there was no significant difference (fH90) compared to the clonal materials. When comparing the clonal materials (TG1 and TG3) at each planting site, they demonstrated similar mechanical properties. The variability in physical and mechanical properties among different genetic materials and planting locations highlights the need to select appropriate teak genetic materials for each region. We concluded that more productive teak clones can be selected without compromising the physical and mechanical properties of the wood.

**Keywords:** heartwood; wood density; clonal teak; fast-growing plantations

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## 1. Introduction

Teak is one of the most valuable tropical hardwoods in the international timber market [1]. Teak wood is preferred in outdoor structures and is used in shipbuilding, laminates, frames, panels, furniture, doors and windows, and household and kitchen artifacts [2]. It is also widely used in the flooring industry, barrels, and sculptures [3]. Such applications require wood to exhibit high dimensional stability under different climatic conditions, attractive and stable coloration, and resistance to xylophagous organisms and weathering [4,5].

The high demand for teak wood, coupled with its high commercial value and the decline in the production of native forests on the Asian continent, has driven the planting of this species in various countries [6]. Currently, fast-growing plantations are prominent worldwide [7]. The global area cultivated with teak has increased considerably, reaching 6.83 million hectares in 2017, with 80% of this area located in Asia, 10% in Africa, and 6% in the Americas [1]. The area of teak plantations (*Tectona grandis* L. f.) in Latin America is estimated to be between 261 and 413 thousand hectares [8]. Among the producing countries in Latin America, Brazil has the largest amount of teak planted [9], with a total of 76 thousand hectares [10].

It is noteworthy that teak is a very demanding species in relation to the soil and climate conditions of the planting sites [11], which limits the proper development of trees intended for the timber market. Soils should be deep and fertile, have good drainage and a pH equal to or greater than 5.5, and have abundant bases, especially calcium; additionally, the site should have a dry period of three to six months, an average annual temperature of 22 to 26 °C, and an average annual rainfall ranging from 1250 mm to 3000 mm [8].

The state of Mato Grosso, Brazil, is known worldwide for its teak plantations, which began in the 1970s [12]. This state, which contains 78% of the teak plantations in the country [13], is located in an area with a tropical climate, which is similar to the place of origin of the species. Considering the climatic, edaphic, and physiographic conditions of Mato Grosso, 63% of the area of the state is suitable or suitable with restrictions for the cultivation of teak, and edaphic factors are the ones that most restrict the growth and productivity of teak in the state compared to climatic factors [14].

Damayanti et al. [15] reported that the lightness intensity (L value) of teak heartwood is lower at drier sites than at wetter sites. Furthermore, they observed that trees in drier sites tend to produce a larger proportion of heartwood, which is more attractive. Souza et al. [16] did not observe variations in teakwood organoleptic properties across different sites in Mato Grosso, Brazil. However, they found that the site significantly influenced fiber and ray parameters, while no significant changes related to vessels were detected. Damayanti et al. [17] noted a consistent wood color in teak trees from the same clone regardless of the growing site. However, they found that the site had a more pronounced effect on wood density, hardness, and radial shrinkage.

In addition to the planting location, genetic factors such as the growth rate, genetic variability among individuals, and susceptibility to pests and disease also directly impact the productivity of teak plantations [18]. Therefore, the search for superior clonal materials has emerged as a strategy for optimizing wood production. Clones can significantly contribute to increased productivity and uniform volume gain, in addition to providing greater heartwood production, a more cylindrical stem shape, a lower presence of buttresses, and technological characteristics related to wood quality factors [19].

The first clonal teak plantations were established in Brazil in the early 2000s [20]. Today, they stand out in relation to seminal materials, and it is evident that clones produce more heartwood at younger ages [21,22]. However, Brazilian research has mainly focused on evaluating the volumetric productivity of clones in different locations [23–25]. Regarding wood quality parameters, studies are usually limited to the quantification of heartwood [21,24]; those related to the wood properties of clonal plantations in Brazil are still incipient [22,26,27].

The teak clones TG1 (or A1) and TG3 (or A3), which were developed by YSG Biotech in conjunction with CIRAD and evaluated in this study, are among the most commonly planted materials in Brazil. Previous studies, such as that by Ugalde-Arias [3], have confirmed that these materials showed significantly greater growth than seminal plantations. In addition, the percentage of heartwood increases with the growth rate of the trees [2,28], which suggests that clonal teak plantations may produce large-diameter logs with a greater proportion of heartwood in relation to seminal plantations. In general, wood from fast-growing plantations is often associated with lower quality due to the concern that rapid tree growth negatively affects wood quality [29].

Although some studies on teak have not shown a significant relationship between growth rate and wood density [30,31], some studies indicate that an increase in the growth rate may result in changes in wood properties [32]. Therefore, it is necessary to better understand the effects of increased tree growth on wood quality in clonal teak plantations. In addition, it is important to evaluate genotype and environmental interactions since notable differences in teak wood quality are observed at different planting sites [27].

This research aimed to elucidate the impact of genetic material and planting site factors and their interactions on the growth and quality of teak wood. Specifically, we are interested in analyzing the variability in morphological parameters such as the diameter and heartwood proportion, density, shrinkage, and mechanical properties of wood. We hope that by better understanding how different genetic materials respond to planting location, the results of this study will have significant practical implications, both for volumetric productivity and for the quality of teak wood, for greater utilization and added value of the final product. This paper will contribute to the development of phenotypic characterization tools for forest genetic improvement programs. This will enable a more assertive selection of superior genetic materials given the wide diversity of soil and climatic conditions found in teak plantations in Brazil and worldwide. To this end, the objective of this study was to investigate the morphological parameters of trees, as well as the physical and mechanical properties of teak wood from two clones (TG1 and TG3) and seminal material at 13 years of age from commercial monocultures located in two municipalities, Nova Maringá and Água Boa, Mato Grosso, Brazil.

## 2. Materials and Methods

### *2.1. Place of Study and Material Collection*

The study material was *Tectona grandis* L. f. wood from commercial plantations with seminal genetic material and two clones (TG1 and TG3) in monoculture. The age of the trees on the collection date (August 2021) was 13 years, and the plantations were located in the municipalities of Água Boa (13°59′43.7″ S, 52°23′57.9″ W) and Nova Maringá (12°29′30.534″ S, 57°8′51.364″ W), Mato Grosso, Brazil (Figure 1).

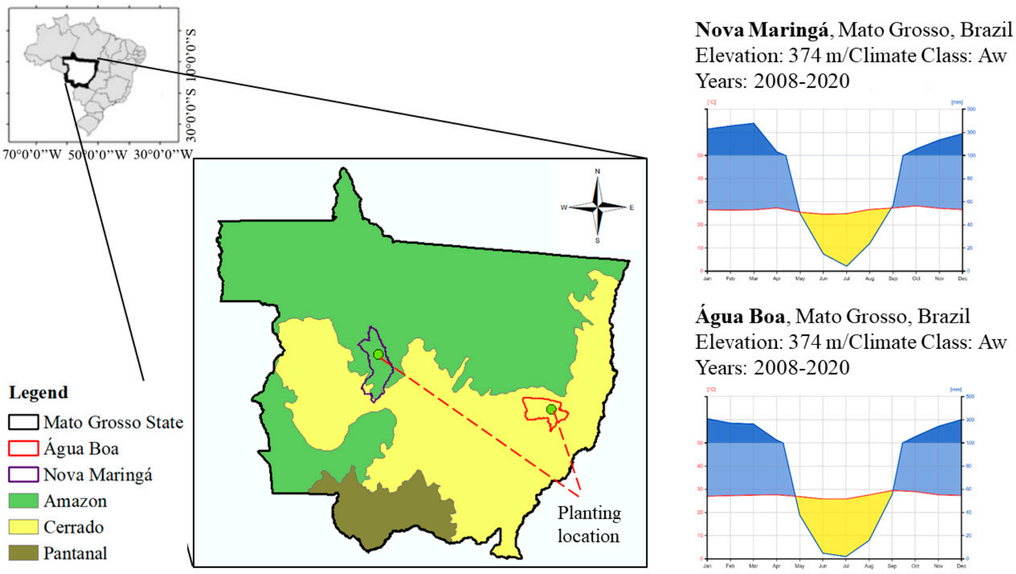


**Figure 1.** Location, mean monthly rainfall, and mean temperature data from 2008 to 2020 for the two planting sites of clonal and seminal *Tectona grandis* in Mato Grosso, Brazil. Climatic data: Zepner et al. [33]: Blue line indicates average precipitation; red line indicates the average temperature; dark blue area indicates precipitation > 100 mm·month$^{-1}$; light blue area indicates precipitation between 50–100 mm·month$^{-1}$; yellow area indicates precipitation < 50 mm·month$^{-1}$.

At each site, we selected five trees per genetic material, representative of the mean diameter of each stand, under adequate health conditions and without visual defects. The mean values of the dendrometric variables are described in Table 1.

**Table 1.** Mean diameter at breast height (DBH), commercial height (CH), and total height (TH) of trees of the different genetic materials of *Tectona grandis* at 13 years of age planted in Água Boa and Nova Maringá, Mato Grosso, Brazil.

| Variables | Água Boa | | | Nova Maringá | | |
|---|---|---|---|---|---|---|
| | TG1 | TG3 | Seminal | TG1 | TG3 | Seminal |
| DBH (cm) | 23.06 (1.46) | 21.21 (0.67) | 21.35 (1.22) | 28.42 (4.26) | 30.26 (2.03) | 29.28 (1.61) |
| CH (m) | 13.54 (0.68) | 14.41 (0.50) | 14.09 (1.01) | 15.38 (2.08) | 14.91 (2.08) | 11.18 (1.04) |
| TH (m) | 18.84 (0.62) | 18.47 (0.60) | 17.26 (1.00) | 22.00 (0.51) | 21.46 (0.34) | 19.92 (0.72) |

(. . .): standard deviation.

Água Boa is located in the Brazilian cerrado region. Its soils are classified as cambisols and oxisols [34]. The area has an average altitude of 357 m above sea level and an Aw climate (tropical climate, with dry winters) according to the Köppen–Geiger classification. The average annual rainfall is 1801 mm, concentrated from September to April, with a dry period of four months (May to August) [33]. The mean annual temperature is 26.8 °C [33].

Nova Maringá is situated in the Amazon biome and is characterized by oxisols [34]. The average altitude is 341 m with an Aw climate. The average annual rainfall is 1917 mm, with a dry period of four months (May to August) [33]. The mean annual temperature is 26.1 °C [33]. A comparison of the soil attributes is presented in Table 2.

**Table 2.** Chemical and granulometric attributes of the soil (0–20 cm layer) at the two planting sites of clonal and seminal *Tectona grandis* in Mato Grosso, Brazil.

| Soil Attributes | Units | Planting Sites | |
|---|---|---|---|
| | | Água Boa * | Nova Maringá ** |
| pH ($CaCl_2$) | - | 5.1 | 4.5 |
| P (Mehlich$^{-1}$) | $mg·dm^{-3}$ | 1.4 | 2.3 |
| K | | 14.5 | 10.5 |
| Ca | $cmol_c·dm^{-3}$ | 1.6 | 5.5 |
| Mg | | 0.7 | 2.8 |
| $Al^{3+}$ | | 0.1 | 0.1 |
| H + Al | | 2.0 | 3.6 |
| SB | | 2.2 | 7.4 |
| t | | 2.3 | 8.3 |
| T (pH = 7.0) | | 4.2 | 10.3 |
| m | % | 7.3 | 1.4 |
| V | | 53.1 | 69.7 |
| B | $mg·dm^{-3}$ | N/A | 1.6 |
| Cu | | N/A | 0.3 |
| Fe | | N/A | 1.2 |
| Mn | | N/A | 2.7 |
| Zn | | 3.8 | 0.7 |
| OM | $g·dm^{-3}$ | 18.5 | 46.9 |

**Table 2.** *Cont.*

| Soil Attributes | Units | Planting Sites | |
|---|---|---|---|
| | | Água Boa * | Nova Maringá ** |
| Clay | $g \cdot kg^{-1}$ | 205.0 | 1.1 |
| Silt | | 65.0 | 13.6 |
| Sand | | 730.0 | 985.7 |

* Soil analysis carried out in 2014–2015; data were provided by the Vale do Araguaia Company (Água Boa, Brazil). ** Soil analysis carried out in 2019, available at Gava [35]. The soil analysis corresponded to a 0–20 cm layer. The basic cations included potassium (K); calcium (Ca); magnesium (Mg); aluminum ($Al^{3+}$); potential acidity (H + Al); the sum of the bases (SB); effective cation exchange capacity (t); total cation exchange capacity (T); aluminum saturation (m); base saturation (V); the micronutrients boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn); organic matter (OM); and N/A = not applicable. The analyses were conducted following the methodology of Teixeira et al. [36].

Five-centimeter-thick disks were removed from each tree collected at the base and every 2.3 m in height up to 11.5 m, which corresponds to the standard assortment of traded logs (Figure 2). These disks represent the beginning and end of each commercial log. These parameters were used to determine the mean diameter and heartwood diameter of the trees.

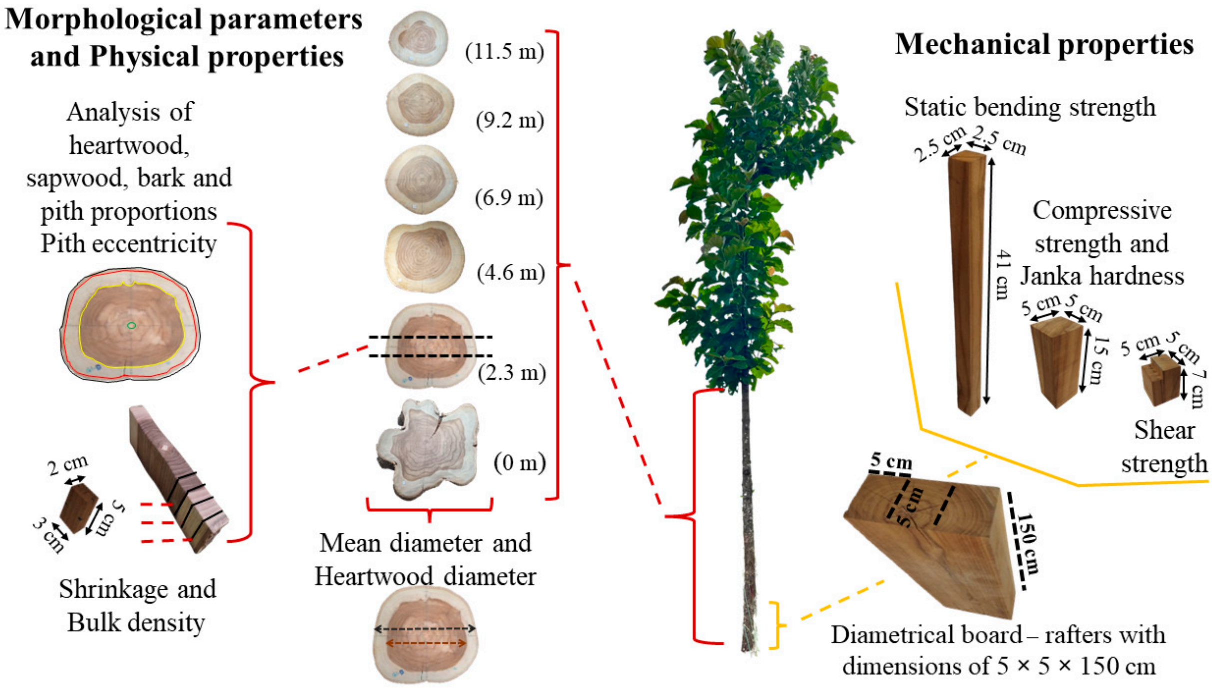


**Figure 2.** Sampling methodology and specimens for wood evaluation of different genetic materials of *Tectona grandis* at 13 years of age planted in Nova Maringá and Água Boa, Mato Grosso, Brazil.

We performed the other evaluations on the discs corresponding to a height of 2.3 m. This height was chosen for the analysis because it represents the end of the first commercial log, which has the highest commercial value in the tree and does not have buttresses. We determined the percentages of bark, sapwood, heartwood, and pith, as well as pith eccentricity, apparent density, and shrinkage (Figure 2). For apparent density and shrinkage, three specimens were prepared from discs positioned in the outer (sapwood), intermediate (outer heartwood), and inner (inner heartwood) regions, as shown in Figure 2.

A log measuring 1.5 m in height was removed from each tree between the base and 2.3 m. From this log, a diametrical board was extracted, from which rafters with dimensions of 5 cm × 5 cm × 150 cm were made. Specimens were randomly selected from the rafters, which were oriented radially (Figure 2). For this purpose, the pith, bark, and defective parts, such as those containing knots and cracks, were discarded. From the resulting rafters, 12 specimens were prepared per tree for the mechanical tests of compressive strength parallel to the fibers, shear strength, static bending strength, and Janka hardness (Figure 2).

### 2.2. Morphological Parameters

All the discs surfaces were sanded and polished with 80-, 120-, 200-, 300-, and 400-grit sandpaper. We marked perpendicular lines passing through the pith and then photographed the discs on a millimeter scale. Using open source software ImageJ software version IJ 1.46r [37], we measured the total diameter with bark, total diameter without bark, heartwood diameter, and pith diameter for all discs. The regions were delimited macroscopically through the differentiation of color between sapwood and heartwood (see discs in Figure 2). For the disc at 2.3 m, the percentages of bark, heartwood, sapwood, and pith were calculated in relation to the total area.

The pith eccentricity was evaluated following the method proposed by Lima et al. [38]. The pith displacement was calculated as the difference between the largest radius, which represents the greatest distance between the pith and the bark, and the mean radius, which is the average of four perpendicular rays between the pith and the bark. The pith eccentricity was then calculated as the ratio of the pith displacement to the mean disc diameter.

### 2.3. Physical Properties

The air-dry density and shrinkage were determined according to ABNT [39] for specimens measuring 2 cm × 3 cm × 5 cm (tangential × radial × longitudinal). We measured the mass (using a digital scale with a precision of 0.01 g) and the radial, tangential, and longitudinal dimensions (using a digital caliper with a precision of 0.01 mm) of each specimen: (1) in hygroscopic equilibrium—relative humidity (RU) = 65% and temperature (T) = 20 °C, moisture content (MC)~12%; (2) after water saturation; and (3) after drying in an oven with forced air circulation (103 ± 2 °C).

The air-dry density (MC~12%) was calculated as the mass-to-volume ratio at hygroscopic equilibrium (RU = 65%; T = 20 °C). The radial, tangential, and longitudinal shrinkage and volumetric variation were obtained according to ABNT [39]. We calculated the anisotropy factor as the ratio between the tangential and radial shrinkage.

### 2.4. Mechanical Properties

The dimensions of the 12 small clear specimens per treatment used for the mechanical tests (Figure 2) were as follows: ABNT [39] for compressive strength parallel to the fibers (5 cm × 5 cm× 15 cm), shear strength (5 cm × 5 cm × 7 cm), and Janka hardness (5 cm × 5 cm × 15 cm); ASTM [40] for static bending strength (2.5 cm × 2.5 cm × 41 cm). Prior to the mechanical tests, we placed the specimens in an acclimatized room (RU = 65%; T = 20 °C) until they reached constant mass (MC~12%). Subsequently, we measured the dimensions (width, thickness, and height) of each specimen and their masses on a scale (precision of 0.01 g) with a digital caliper (accuracy of 0.01 mm).

The tests were performed on an Amsler Wolpert universal testing machine following the guidelines of ABNT [39] for determining compressive strength parallel to the fibers, shear strength, and Janka hardness and ASTM [40] for static bending. For Janka hardness, we penetrated a 1 $cm^2$ semisphere in the direction normal to the wood fibers without differentiating between the radial and tangential sections.

### 2.5. Statistical Analysis

The experiment was performed with a completely randomized design in a factorial arrangement with two factors (genetic material and planting location) and five replicates (trees) for the morphological parameters and physical and mechanical assays. The genetic material (clones TG1, TG3, seminal material) and planting location (Nova Maringá, Água Boa) were considered qualitative factors.

For the morphological parameters (mean and heartwood diameters), a factorial arrangement with three factors (genetic material, planting site, and stem height) and four replicates (trees) was used. In this case, genetic material and planting location were considered qualitative factors, and stem height was considered quantitative.

The results of the analyses were subjected to an analysis of variance (ANOVA). When significant differences were established ($p$ value < 0.05), Tukey's test was performed for the qualitative factors, and linear regression analysis was performed for the quantitative factors. For this purpose, the model with the best estimation parameters and the highest adjusted coefficient of determination ($R^2$) was selected. The analyses were performed using R software, version 4.3.1 [41].

To determine the correlations between air-dry density, mean diameter (2.3 m), and physical and mechanical properties, Pearson's correlation coefficient was used ($p \leq 0.05$).

## 3. Results and Discussion

### 3.1. Morphological Parameters

Significant interactions were detected for the mean diameter and heartwood diameter between the planting site and genetic material, as well as between the planting site and stem height ($p < 0.05$) (Figure 3). No significant interaction was found between genetic material and stem height.

When analyzing the relationship between local and genetic material, the mean diameters were significantly greater in Nova Maringá (Figure 3A) for all the genetic materials evaluated. The TG3 clone, the seminal material, and the TG1 clone exhibited mean diameters 35.7%, 30.6%, and 29% greater, respectively, than those observed in Água Boa. These results indicate a faster growth rate of teak trees in Nova Maringá. In addition, in this municipality, both clones, TG1 and TG3, had a mean diameter significantly greater than that of the seminal material. However, in Água Boa, only the TG1 clone stood out, presenting an average diameter 10% larger than that of the TG3 clone and the seminal material.

This same trend was observed for the heartwood diameter (Figure 3B). A significant and positive relationship between the tree diameter and heartwood diameter for teak has been reported in previous studies [24,28,42,43]; thus, it is possible to estimate the heartwood diameter from the total diameter of the tree [44]. Fast-growing conditions produce large-diameter logs but also result in greater amounts of heartwood [44].

In a study of teakwood by Lemos et al. [21], which was performed on 6-year-old trees, and by Curvo et al. [22], which was performed on 10-year-old trees, larger diameters and percentages of heartwood were observed for clonal material than for seminal material. These findings support the results obtained for clonal plantations with appropriately selected genetic material.

The mean (Figure 3C) and heartwood (Figure 3D) diameters along the stems of the Nova Maringá trees were significantly greater than those of the Água Boa trees, regardless of the genetic material. Regarding the mean diameter, the most significant differences were at the base (32%) and at the 11.5 m height (42%). This highlights the greater productivity of the Nova Maringá trees, which allowed for better use of the wood until the fifth log (9.2–11.5 m) of the 13-year-old trees already had an average diameter greater than 15 cm.

The heartwood diameter tended to decrease along the stem (Figure 3D), corroborating the findings of Fernández-Sólis et al. [45]. Comparing the planting sites, the heartwood diameter of trees from Nova Maringá was greater at all heights evaluated, ranging from 25 cm (base) to 11 cm (11.5 m), while for trees from Água Boa, the diameter of the heartwood length ranged from 20 cm (base) to 3.48 cm (11.5 m).

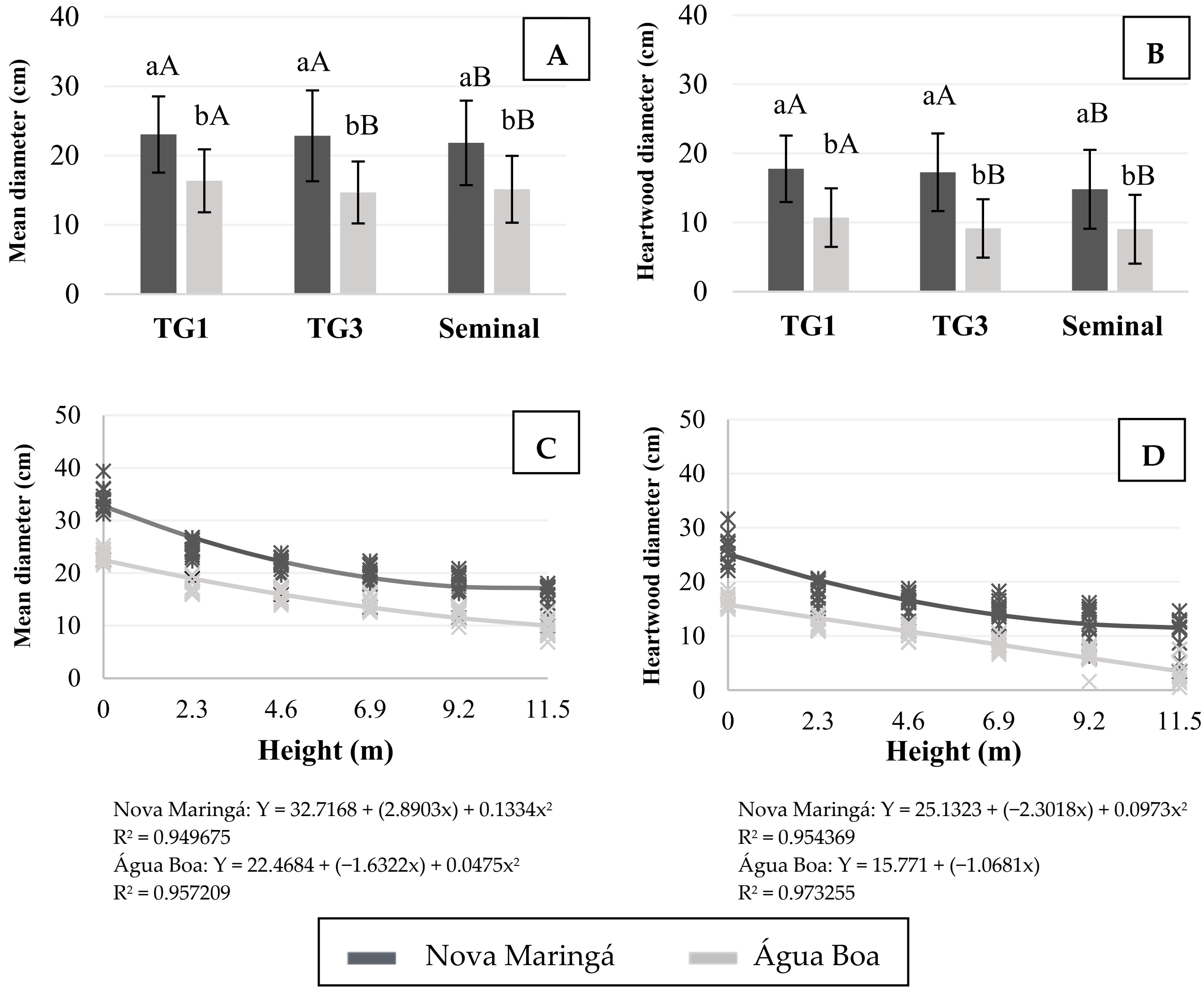


**Figure 3.** Mean and heartwood diameters of the genetic material (**A**,**B**) and along the stem (**C**,**D**) of *Tectona grandis* trees at 13 years of age according to the planting site in Mato Grosso, Brazil. Means followed by the same letter were not significantly different according to Tukey's test ($p < 0.05$). Lowercase letters represent significant differences at the site within the genetic material, and capital letters represent significant differences in the genetic material within the site. The bars correspond to the standard deviation.

Considering the commercialization of teak wood in blocks, for the trees of Nova Maringá, aged 13 years, it would be feasible to produce heartwood teak blocks of 15 cm × 15 cm in the first two logs (base–2.3 m and 2.3 m–4.6 m) and 10 × 10 cm in the other three logs. On the other hand, Água Boa trees generated 10 cm × 10 cm heartwood teak blocks in the first two logs. In the other logs, there was a small proportion of heartwood, preventing the production of heartwood blocks. This is justified by the preference and appreciation in the international market of woods with a more significant proportion of heartwood [28]. Notably, the clonal materials tended to have greater heartwood production, especially TG1 and TG3 for Nova Maringá and TG1 for Água Boa.

Since the same genetic materials were evaluated in the two planting sites at the same age (13 years), the largest diameters observed for the trees from Nova Maringá can be attributed to edaphoclimatic factors. The annual rainfall was approximately 100 mm greater in Nova Maringá (Figure 1) than in Água Boa. The two sites exhibited annual precipitation and seasonality of 1200–2500 mm and within 3 to 5 months of the dry season, which is within the optimal range for teak development, as defined by Kollert and Kleine [1].

However, the soil attributes differed between the sites (Table 2), which may have contributed more to tree growth. It is important to note that both sites have a pH below the ideal value for teak cultivation, which, according to Moraes Neto [8], is 5.5. However, studies carried out on commercial plantations with these two teak clones (TG1 and TG3) in different Latin American countries revealed that these clones, unlike the material from seeds, adapt and grow in acidic soils with pH values between 4.0 and 4.5 [3]. Additionally, according to Favare et al. [46], the greatest plant development and nutrient accumulation occur when the base saturation (V) is between 60 and 80%. In this sense, the soil of Nova Maringá has greater base saturation (69.7) than that of Água Boa (53.1) (Table 2), which indicates that more nutrients are available.

The soil of Nova Maringá also showed a lower percentage of aluminum saturation (m) than that of Água Boa (Table 2). Because aluminum causes a reduction in root growth and development, its lower presence in Nova Maringá favors plant development [47]. In addition, more organic matter (OM) was observed in Nova Maringá than in Água Boa (Table 2). In a study in the state of Mato Grosso, Brazil, Medeiros [14] also indicated that Nova Maringá was a more suitable region for teak cultivation than was Água Boa, supporting the results of this study, which showed a greater growth rate for teak in the municipality of Nova Maringá.

The percentages of bark, sapwood, heartwood, and pith, determined at a height of 2.3 m, were analyzed in a factorial scheme with two factors (planting location × genetic material), and the mean values are shown in Figure 4. There was a significant interaction ($p < 0.05$) between the factors for bark percentage only. For the other parameters, the genetic material and planting location factors were evaluated independently.

For the bark percentage, the highest average value (14.75%) was observed for the TG3/Água Boa clone. At this planting site, the bark percentage of clone TG3 was significantly greater than that of the other genetic materials. In Nova Maringá, there was no significant difference in these parameters when comparing the materials. There was a greater percentage of bark in the Água Boa than in the Nova Maringá clonal material. However, for the seminal material, the percentage of bark was statistically the same in both municipalities.

This greater percentage of bark in trees in Água Boa (Figure 4A) may be due to their lower diameter growth compared to that in Nova Maringá (Table 1, Figure 3). In teak trees, the smaller the diameter of the stem is, the greater the percentage of bark [48]. This is expected because cambium cells produce more wood, and less nutrients are destined for bark production [49,50]. Additionally, the higher percentage of bark in Água Boa can also be attributed to its lower precipitation and the highest average annual temperature.

A lower percentage of bark is desirable since the bark is a residue of the production process. Thus, the clonal trees produced in Nova Maringá were notable for this parameter. However, according to Baptista et al. [51], residual teak bark can be used as a raw material for bioprocessing due to the volume generated and its anatomical characteristics and chemical composition.

Planting location significantly influenced the percentages of sapwood (Figure 4B) and heartwood (Figure 4D), regardless of the genetic material. In Nova Maringá, the trees had, on average, 56.07% heartwood, while in Água Boa, this value was less than 50% (Figure 4D). Factors such as climatic conditions, growth rate, physiological processes, and age affect heartwood formation and the heartwood/sapwood ratio in trees [52]. In Nova Maringá, there was greater annual rainfall (Figure 1) and more favorable soil conditions (Table 2) for growth (Table 1, Figure 3), with the percentage of heartwood being directly related to the diameter of the trees [28,53,54].

Regarding genetic factors, the percentage of sapwood in the seminal trees was approximately 5% greater than that in the TG1 and TG3 clonal materials (Figure 4C). This is due to the faster growth rate of the clonal materials, resulting in a larger diameter of the trees (Figure 3) and, consequently, greater formation of heartwood. The seminal material had the lowest percentage of heartwood (49.2%), while the clonal material TG1 had the highest percentage (54.18%) (Figure 4E), regardless of the planting location. Curvo et al. [22] obtained similar results for 10-year-old teak trees.

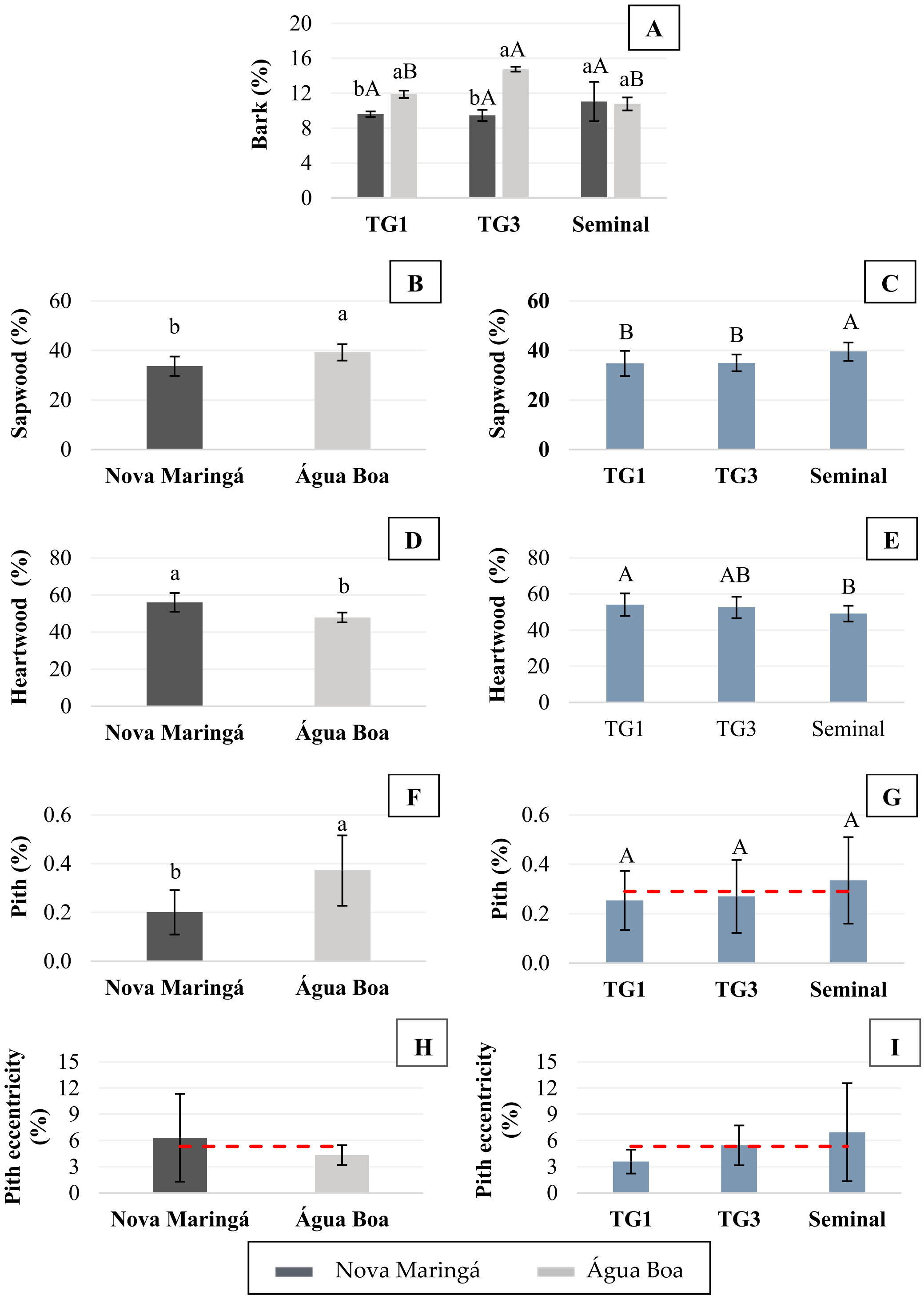


**Figure 4.** Percentages of bark (**A**), sapwood (**B**,**C**), heartwood (**D**,**E**), pith (**F**,**G**) and pith eccentricity (**H**,**I**) at a height of 2.3 m for different genetic materials of *Tectona grandis* trees planted in Nova Maringá and Água Boa, Mato Grosso, Brazil. Means followed by the same letter were not significantly different according to Tukey's test ($p < 0.05$). For the bark (%), lowercase letters represent a significant difference at the site within the genetic material, and capital letters represent a significant difference in the genetic material within the site. The bars correspond to the standard deviation. Red dashed lines indicate the mean values.

This suggests that clonal plantations may be more advantageous by properly selecting superior genetic materials, providing higher percentages of heartwood even at intermediate ages. Considering the natural durability and attractiveness of coloration, heartwood constitutes a commercially valuable part of the teak stem [28,55,56]. Thus, teak trees with a greater percentage of heartwood have greater demand and appreciation.

The pith percentage was significantly greater in Água Boa than in Nova Maringá (Figure 4F), regardless of the genetic material. In turn, the percentage of genetic materials, regardless of the planting site (Figure 4G), was 0.28% (standard deviation = 0.04), which was not significantly different. Berrocal et al. [53] reported a mean pith percentage equal to 0.42% for a teak monoculture at 13 years of age, which is close to that found in the present study. It is important to verify the percentage of pith in logs because its presence affects the mechanical strength and quality class of sawn wood [27,44]. Considering this parameter, the teak woods from the plantations evaluated at percentages lower than 1% are suitable for the commercialization and production of sawn pieces.

There was no significant difference ($p < 0.05$) in pith eccentricity, either for the planting site (Figure 4H) or for the genetic material factor (Figure 4I), resulting in an average value equal to 5.33%. This parameter is used to evaluate the resulting effect of growth stresses due to terrain slope, winds, and genetic factors [57].

Notably, the highest standard deviation (5.61) in pith eccentricity was observed for the seminal material (Figure 4I). This result shows that genetic improvement through the use of clonal materials contributes to reducing the heterogeneity of this property. Albuês et al. [26] also found no significant difference in the genetic materials but a greater variation in the seminal material. Low eccentricity variation is important for industrial processing because it promotes greater standardization of activities, resulting in gains in productivity and sawn wood yield. An eccentric pith causes tension wood [11], and values above 20% favor the appearance of defects such as cracks and warping [58]. Thus, the average values of pith eccentricity (Figure 4H,I) indicate that the genetic materials evaluated, regardless of the planting site, are suitable for lumber production.

### 3.2. Physical and Mechanical Properties

Air-dry density (MC~12%) was significantly influenced by planting location and genetic material, with a significant interaction between these factors (Figure 5).

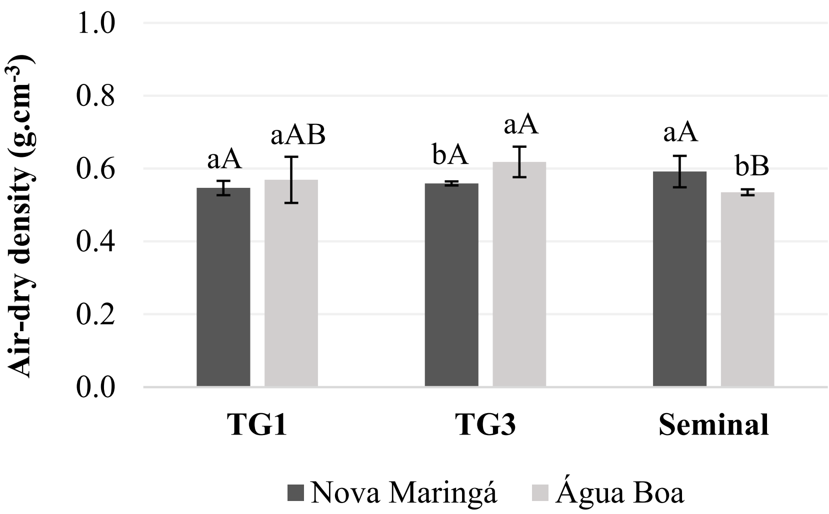


**Figure 5.** Wood air-dry density at hygroscopic equilibrium moisture content (~12%) of different genetic materials of *Tectona grandis* at 13 years of age planted in Nova Maringá and Água Boa, Mato Grosso, Brazil. Means followed by the same letter were not significantly different according to Tukey's test ($p < 0.05$). Lowercase letters represent significant differences at the site within the genetic material, and capital letters represent significant differences in the genetic material within the site. The bars correspond to the standard deviation.

Considering the local factor, the evaluated genetic materials showed no significant difference in wood air-dry density in Nova Maringá. In Água Boa, clone TG3 had the highest density (0.618 g·cm$^{-3}$), while the seminal material had the lowest value (0.535 g·cm$^{-3}$) (Figure 5). When considering the genetic material, the seminal wood from Nova Maringá had a greater density, approximately 10%, than the seminal material from Água Boa. For the clonal materials, the TG1 clone had no difference between the locations, while the TG3 clone planted in Água Boa showed a 9.56% greater density compared to the same material from Nova Maringá. Thus, there was no pattern of variation in the apparent density in relation to the genetic material and planting location for the 13-year-old trees evaluated.

Using X-ray densitometry, Curvo et al. [22] did not observe any difference in the air-dry density of clonal or seminal material in teak wood at 10 years of age. Souza [59], for teak wood at 14 years of age obtained from plantations in Alta Floresta and Nossa Senhora do Livramento, Mato Grosso, Brazil, found no differences between locations, with mean air-dry density values ranging from 0.557 to 0.596 g·cm$^{-3}$, which are similar to those found in the present study.

Despite the conditions of the studied locations (Figure 1; Table 2) influencing the growth of teak trees (Figure 3), these sites did not uniformly influence the density of genetic materials. Clonal materials exhibited lower density in Nova Maringá, where soil properties are more favorable for teak development, while seed material had lower density in Água Boa, where soil properties are inferior. The mean air-dry density for all sampled trees was 0.570 g·cm$^{-3}$ (standard deviation = 0.0433), with a marginal but significant difference, with higher and lower means observed for trees from Água Boa (Figure 5). Moya et al. [60] reported that density was the parameter least correlated with the physical and chemical properties of soil. Amoah and Inyong [61] assessed the influence of planting site, tree age, and trunk position and found that location accounted for only 1.2% of the total density variation. Other studies, such as those by Hidayati et al. [62] and Moya and Perez [63], stated that there was no influence of location or environment on teak wood density.

Teak wood at 13 years of age, regardless of the genetic material and the planting site, is classified as having moderate density. Density is an important quality parameter for wood use indication. Given that density has a direct effect on the operational and economic performance of various production processes, the studied wood is recommended for use in interior furniture, doors, sculptures, and light civil construction, which are the traditional uses of teak wood.

For shrinkage, there was no significant interaction, and the genetic material and planting location factors were evaluated independently (Table 3).

**Table 3.** Shrinkage of wood of different genetic materials of *Tectona grandis* at 13 years of age planted in Nova Maringá and Água Boa, Mato Grosso, Brazil.

| Shrinkage (%) | Genetic Material | | | Planting Sites | |
|---|---|---|---|---|---|
| | TG1 | TG3 | Seminal | Nova Maringá | Água Boa |
| Longitudinal | 0.30 A (0.07) | 0.32 A (0.08) | 0.30 A (0.10) | 0.33 a (0.08) | 0.28 a (0.07) |
| Tangential | 5.48 A (0.39) | 5.91 A (0.36) | 4.74 B (0.41) | 5.27 a (0.66) | 5.48 a (0.58) |
| Radial | 2.39 A (0.46) | 2.45 A (0.47) | 2.13 A (0.11) | 2.15 b (0.14) | 2.50 a (0.48) |
| Volumetric | 8.02 A (0.68) | 8.51 A (0.54) | 7.05 B (0.38) | 7.61 b (0.68) | 8.10 a (0.88) |
| Anisotropy factor | 2.36 A (0.33) | 2.54 A (0.53) | 2.27 A (0.12) | 2.48 a (0.24) | 2.29 a (0.46) |

(...): standard deviation. Means followed by the same letter, uppercase for material and lowercase for planting site, did not differ statistically from each other according to Tukey's test ($p < 0.05$).

Compared with the seminal material, the clonal materials were less stable, with 17% greater tangential shrinkage and 15% greater volumetric variation (Table 3), regardless of the planting site. It was observed that the wood of trees grown in Nova Maringá showed greater dimensional stability, with a 14% lower radial shrinkage and a 6% lower volumetric variation compared to those of Água Boa, regardless of the genetic material. Notably, for the local factor, for the genetic material, no significant differences were found in the longitudinal shrinkage (0.31%) or in the anisotropy factor (2.39). Additionally, there were no significant differences in tangential shrinkage for the local factor (5.37%) or in radial shrinkage for the genetic material factor (2.32%).

The highest values of volumetric variation were observed in the clonal materials, which generally presented larger mean diameters in relation to the seminal material (Figure 3). However, the highest values of volumetric variation were also recorded in wood from Água Boa, whose tree growth was significantly lower than that of Nova Maringá (Figure 3). Thus, no pattern was observed between diameter growth and the shrinkage of teakwood in these fast-growing plantations, and it is not possible to determine whether there was a direct relationship between these two parameters.

The wood from Nova Maringá, regardless of the genetic material, and the material of seminal origin, regardless of the planting location, stood out due to the lower volumetric variation. However, considering that the differences in the anisotropy factor were not significant ($p < 0.05$) regardless of the genetic material and planting location, the evaluated teak woods can be considered to have similar shrinkage. The wood quality was classified as "poor" for uses that do not allow defects due to an anisotropy factor greater than 2.0 [64].

It is noteworthy that the teak wood evaluated does not fit the traditional characterization of having high dimensional stability, as observed in native forests and slow-growing plantations. Woods from fast-growing trees (growth ring width > 5 mm) showed significantly greater radial shrinkage than slow-growing woods (growth ring width > 5 mm) [65]. Wanneng et al. [66] reported a mean anisotropy factor of 1.60 for 10- to 25-year-old wood from trees planted in Laos.

Silva et al. [27], in a literature review on teak wood from different regions of Brazil and of different ages, reported values of 1.20 to 2.79 for the anisotropy factor and 4.41 to 9.83% for the volumetric variation. The values found in this study are within these limits. Therefore, it is worth noting that woods of clonal origin (TG1 and TG3) may offer advantages because of their faster growth compared to that of seminal material (Figure 3) while maintaining acceptable shrinkage.

Regardless of the genetic material, lower values of radial shrinkage and volumetric variation were found for teak wood obtained in Nova Maringá (Table 3), indicating that better soil attributes (Table 2), which promote greater tree growth, resulting in lower values for these properties. However, for other stability parameters, this relationship does not apply. Despite the studies by Moya et al. [60], Moya and Perez [63], and Gutiérrez et al. [67], which reported differences in the average values of several shrinkage parameters of teak wood obtained from different locations, the authors assert that soil characteristics (physical and chemical) do not significantly influence wood properties. Variations in wood properties cannot be fully explained by soil characteristics, physical or chemical conditions, and other factors, such as genetics, management type, dry months of the year, and precipitation, among others, as suggested by Moya et al. [60].

For the mechanical tests, there was a significant interaction between the genetic material and planting site (Table 4).

In general, it was observed that in Nova Maringá, the wood of the seminal material had higher mean values; that is, it was more resistant than the clonal materials. On the other hand, the wood of the Água Boa seminal material was less resistant (fv0, fm, and fc0), or there was no significant difference (fH90) in relation to the clonal materials. When comparing the clonal materials (TG1 and TG3) at each planting site, they showed similar mechanical properties.

**Table 4.** Mechanical properties of wood of *Tectona grandis* of different genetic materials at 13 years of age planted in Nova Maringá and Água Boa, Mato Grosso, Brazil.

| Mechanical Tests | | Genetic Material | | |
|---|---|---|---|---|
| | | TG1 | TG3 | Seminal |
| fv0 | Nova Maringá | 8.63 bB (1.02) | 9.01 bB (0.38) | 10.42 aA (1.13) |
| | Água Boa | 9.83 abA (0.73) | 10.62 aA (0.83) | 8.69 bB (0.59) |
| fm | Nova Maringá | 77.80 bA (5.05) | 82.63 abA (9.66) | 85.84 aA (8.68) |
| | Água Boa | 81.33 abA (5.84) | 86.76 aA (5.34) | 74.67 bB (12.25) |
| fc0 | Nova Maringá | 43.62 bB (2.82) | 44.69 bA (2.55) | 48.44 aA (3.37) |
| | Água Boa | 46.10 aA (1.98) | 46.38 aA (2.44) | 40.45 bB (2.28) |
| fH90 | Nova Maringá | 3.45 bB (249.11) | 3.57 bA (360.73) | 4.42 aA (428.84) |
| | Água Boa | 4.23 aA (378.43) | 3.92 aA (246.41) | 4.00 aB (223.20) |

fv0: shear strength (MPa); fm: static bending strength (MPa); fc0: compressive strength parallel to the fibers (MPa); fH90: Janka hardness (kN). (...): standard deviation. For the same parameter, the same lowercase letters in the row and capital letters in the column did not differ from each other according to Tukey's test ($p < 0.05$).

The wood of clone TG1 planted in Água Boa was more resistant than that of Nova Maringá; clone TG3 presented statistically similar mechanical properties ($p < 0.05$) when comparing the two sites, except for fv0, where Água Boa stood out; and the seminal material showed better results in Nova Maringá in relation to Água Boa for all the mechanical properties evaluated (Table 4).

These observations highlight that the mechanical strength of teak wood varies significantly among different genetic materials and planting locations, underscoring the importance of selecting suitable genetic materials for each region. Furthermore, it was found that higher growth rates (Figure 3) are not associated with lower mechanical strength (Table 4). Regardless of the genetic material, the trees from Nova Maringá had greater growth than did those from Água Boa (Figure 3), without resulting in a decrease in mechanical properties (Table 4). When comparing the genetic materials, clones TG1 and TG3 stood out in terms of growth in relation to the seminal material in Nova Maringá, and in Água Boa, TG1 stood out (Figure 3), which also did not have a direct relationship with the mechanical properties. This indicates that more productive clones can be selected and/or that the rotation cycle of fast-growing teak can be reduced without compromising the mechanical strength of teak wood [2].

The mean results of the mechanical properties (Table 4) are similar to those found in previous studies that evaluated teak wood planted in Brazil. Albuês et al. [26] reported shear strength values ranging from 9.48 MPa (clonal material) to 10.61 MPa (seminal material) in wood from 15-year-old trees. Regarding the static bending strength, Benedetti [68] reported values close to 89 MPa, and Souza [59] reported values ranging from 98 to 101 MPa for 14-year-old teak. Blanco-Flórez et al. [57] reported a value of 46.58 MPa for 13-year-old teak, and Albuês et al. [26] reported a value of 46.18 MPa for compressive strength parallel to the fibers. For Janka hardness, Blanco-Flórez et al. [57] reported a hardness of 4.66 kN, and Albuês et al. [26] reported a hardness of 4.30 kN. The low hardness values indicate that the evaluated wood is unsuitable for use, such as floors and decking.

Our results indicate that 13-year-old teak trees from Nova Maringá and Água Boa, MT, Brazil, show slightly lower density and mechanical values than mature trees. For example, a study carried out by Thulasidas and Bhat [69] on 35-year-old teak trees from Kerala, India, indicated air-dry densities of 0.631 $g/cm^3$, fm = 111.20 MPa, and fc0 = 55.5 MPa. Similarly, Rizanti et al. [70] studied 40-year-old teak trees from Java, Indonesia, and reported air-dry densities of 0.664 $g/cm^3$ and fm = 118.90 MPa. In addition, Darmawan et al. [71] reported that 40- to 60-year-old teak trees from Java, Indonesia, had air-dry densities of 0.670 $g/cm^3$ and fm = 102 MPa. The mechanical properties should be highlighted because fast-growing plantations with short rotations have been producing an increasing amount of teak wood to supply the timber market. Most of this wood is juvenile, which is synonymous with inferior mechanical properties due to its density [69]. This highlights the importance of selecting and processing teak wood from younger trees to fulfill the standards required for specific applications.

Table 5 shows the correlations between the air-dry density and mean diameter (2.3 m) and between the air-dry density and the physical and mechanical properties.

**Table 5.** Pearson correlations between air-dry density and mean diameter at 2.3 m and the physical and mechanical properties of *Tectona grandis* wood of different genetic materials at 13 years of age planted in Nova Maringá and Água Boa, Mato Grosso, Brazil.

| Planting Sites | | AID | $MD_{2.3}$ | TS | LS | RS | VS | AF | fc0 | fH90 | fv0 | fm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nova Maringá | AID | 1 | −0.59 | −0.23 | −0.44 | −0.31 | −0.32 | −0.20 | 0.74 | 0.28 | 0.23 | 0.68 |
| | $MD_{2.3}$ | | 1 | −0.09 | 0.64 | 0.21 | 0.03 | −0.11 | −0.54 | −0.05 | 0.12 | −0.50 |
| Água Boa | AID | 1 | −0.09 | 0.56 | 0.58 | 0.24 | 0.53 | 0.34 | 0.68 | 0.18 | 0.39 | 0.33 |
| | $MD_{2.3}$ | | 1 | −0.27 | −0.55 | 0.12 | −0.16 | −0.29 | 0.29 | 0.11 | −0.11 | −0.01 |

AID: air-dry density; $MD_{2.3}$: mean diameter at 2.3 m; TS: tangential shrinkage; LS: longitudinal shrinkage; RS: radial shrinkage; VS: volumetric shrinkage; AF: anisotropy factor; fc0: compressive strength parallel to the fibers; fH90: Janka hardness; fv0: shear strength; fm: static bending strength.

According to Table 5, there was a negative correlation between the average diameter and the air-dry density of teak wood at 13 years of age in Nova Maringá (−0.59), i.e., greater growth in diameter results in lower wood density. In Água Boa, this correlation was very weak, indicating that growth does not directly influence density. In Nova Maringá, air-dry density correlated negatively with shrinkage parameters, while in Água Boa, this correlation was increasingly positive. At both sites, there was a positive correlation between density and mechanical properties, especially for fc0. Evaluating the correlation between diameter and shrinkage parameters, longitudinal shrinkage was found to be positive for Nova Maringá and negative for Água Boa. The weak correlations between diameter and the other shrinkage parameters (tangential shrinkage, longitudinal shrinkage, radial shrinkage, volumetric shrinkage, and anisotropy factor) are noteworthy. In Nova Maringá, there was a negative correlation between diameter and fc0 and fm, and in Água Boa, the correlation was positive (0.29) for fc0.

## 4. Conclusions

The findings of this study emphasize the significant impact of both genetic material and planting site on the wood characteristics of teak trees in Mato Grosso, Brazil. Genetic material and planting site independently influence the morphological parameters of teak trees and shrinkage, while air-dry density and mechanical properties are dependent on these factors. Hence, determining the properties of teak wood from various genetic materials under diverse planting conditions, which may influence the market price of wood, is important.

Planting site had a greater influence on diameter growth and heartwood content, while physical and mechanical properties showed less variation among locations. Additionally, clonal materials had physical and mechanical properties similar to the seminal material but had larger diameters and heartwood diameters. Thus, more productive teak clones can be selected without compromising the physical and mechanical properties of the wood.

Based on the mechanical and physical tests, the evaluated 13-year-old teak wood can be used for a variety of purposes, such as furniture, ceilings, doors, decorative panels, and light civil construction. However, it is recommended to continue carrying out studies on the physical–mechanical properties of these clones at ages between 20 and 25 years to better understand the potential of this wood for other products.

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