



Prediction of Basic Wood Density from the Apparent Density of Growth Rings of *Tachigali vulgaris* in Plantations in the Amazonia

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Abstract

Tachigali vulgaris is a fast-growing species adapted to different environmental conditions and has the potential to meet the demand for energy biomass in Amazonia. However, research is needed to guide its management and expand understanding of silvicultural aspects and wood quality. This study aimed to (i) develop an equation to estimate the basic density of wood from the apparent density of *T. vulgaris* growth rings in the Amazonia, and (ii) apply the generated equation to estimate the average and annual basic density along the stems and evaluate the variation of these densities. The research was carried out in Pará, Brazil, in two experimental plantations (without and with P and K fertilization), established in sandy loam and very clayey soil. 32 trees (non-forked and forked) were sampled. Discs approximately 5 cm thick were removed along the stems and divided into duplicates of approximately 2.5 cm. One duplicate was used to determine the wood basic density (WBD) and the other the wood apparent density (WAD). WAD was the only significant explanatory variable of WBD, with a correlation=0.84, coefficient of determination=0.71, root mean square error=9.31, and mean absolute error=7.28. The generated equation ($WBD = 0.7492WAD + 0.0632$) overestimated the WBD by 1.09% on average. Non-forked trees had a higher proportion of wood with density $\geq 0,500 \text{ g cm}^{-3}$. The study suggests that different regions of the tree can be used for different bioenergetic uses. The developed equation can be recommended to convert the apparent density at 12% moisture content into basic density, both for future studies and for application in the forestry sector.

Keywords Density estimation · Forestry · Amazonian species · Wood quality

Introduction

Biomass has gained increasing relevance in the global energy scenario, especially after the oil crisis in the 1970s (Resquin et al. 2019). Among biomass sources, the use of wood, mainly from plantations for energy purposes, may be a viable alternative to replace fossil fuels in the steel industry and thermoelectric power plants (Massuque et al. 2023). Furthermore, one of the alternatives for mitigating CO₂ from anthropogenic activities is the use of planted forests, which consist of a major carbon sink while they provide other environmental, social, and economic benefits (Mada et al. 2022). The sustainable management of forest plantations ensures the supply of biomass (wood) for bioenergy, the production of clean and renewable energy, long-term mitigation of climate change, and the reduction of pressure on natural forests (Myint et al. 2021). In this context, wood density is a physical property that enables the estimation of carbon storage in trees (Chave et al. 2006; Phillips et al. 2019).

The apparent density of wood is the ratio between the mass and volume of a wood sample based on a given moisture content (Dias Júnior et al. 2021; Moraes et al. 2023). In general, this moisture content has a fixed value, such as the international standard of 12% (Sallenave 1955). Thus, the apparent density of wood at 12% moisture content is defined as the ratio between the mass and volume of a wood sample with that same moisture content and can be expressed in g cm⁻³ (Vieilledent et al. 2018). Another widely used measure is basic density (dry weight of wood in a kiln/volume of fully saturated wood), considered a functional characteristic that helps to understand the performance and suitability of species in ecology (Fischer et al. 2026). This important variable can be used in calculating tree and forest biomass in carbon cycle research, as it helps determine the amount of carbon stored per unit volume of stem (Chave et al. 2009; Vieilledent et al. 2018). The basic density of wood has been widely used for ecological purposes, as a basis for calculating the dry biomass of trees from their living volume. In this sense, it is important to convert apparent density to basic density (Vieilledent et al. 2018). In addition, the basic density of wood is technologically important, especially because it is related to mechanical properties such as strength and stiffness (Niklas and Spatz 2010), energy properties such as energy density (Protásio et al. 2019), apparent density of charcoal, and mechanical strength of charcoal (Assis et al. 2016; Lima et al. 2020). Furthermore, density values are affected by anatomical characteristics (e.g., wall thickness, lumen size, proportion of anatomical elements) and/or chemical characteristics, such as extractives, lignin, and cellulose, which affect the amount of mass present in a given volume (Lachenbruch and McCulloh 2014).

One of the main pathways for obtaining biomass for energy use is through energy forests, which are defined as forest plantations of native or exotic species managed to maximize biomass productivity and to achieve suitable technological properties for energy applications, either through direct use or as feedstock for conversion processes, such as carbonization for charcoal production. In this context, energy forests with *Eucalyptus* species are the main source of biomass to produce charcoal for steelmaking purposes in Brazil (Pena-Vergara et al. 2022). However, studies show a loss of crop productivity with rising temperatures and reduced rainfall (Binkley et al. 2020). Moreover, forest plantations, although occupying a large territorial area in

Brazil (10.2 million ha), are incipient in the Amazon region (IBÁ 2024). In this scenario, it is necessary to increase the areas planted with energy crops in the Amazon, as the region is home to the country's second largest producer of pig iron, the Carajás steel complex, located between the states of Pará and Maranhão. In 2023, this complex was responsible for producing 12% of the country's pig iron (SINDIFER 2024). Thus, it is an important challenge to seek new sources of raw material for charcoal production, since energy plantations with exotic species (*Eucalyptus* and *Corymbia*) in the region are incipient, making the use of native species adapted to the region essential to establish forest plantations with high productivity and wood with potential for bioenergy (Santos et al. 2024).

One species that has been reported in the literature as having potential for energy crops in the Amazon is *Tachigali vulgaris* L.F Gomes da Silva & H.C Lima, commonly known as “tachi branco” or “cachamorra-branca”. The species has a wide geographical distribution in South America. In Brazil, it can be found in all regions of the country, except for the South (Carvalho 2005; Van Der Werff 2008). Thus, the species can be used in a wide range of territories in Brazil and other tropical regions of the world with similar soil and climate characteristics, as it adapts well to different environments. Recent studies have demonstrated the species' potential for energy purposes. The basic density values range from 0.443–0.529 g cm⁻³ at 87 months (Barros-Junior et al. 2022) and from 0.486 to 0.597 g cm⁻³ at 102 months (Lima et al. 2023). The energy density of 9151 MJ m⁻³ and heating value of wood of 19.7 MJ kg⁻¹ at 87 months (Silva et al. 2021). Furthermore, *T. vulgaris* shows fast growth, with height increment of 2.38 m year⁻¹ and diameter increment of 2.73 cm year⁻¹ at 102 months (Lima et al. 2023), and mean annual increment of 23.22 m³ ha⁻¹ year⁻¹ at 102 months (Moraes et al. 2023) and 25.80 m³ ha⁻¹ year⁻¹ at 120 months (Teixeira et al. 2023) at 3 × 2 m spacing.

To date, there are no commercial plantations of *T. vulgaris* in Brazil (Teixeira et al. 2023). Therefore, in order to enable its future use for energy crops on the Amazon, it is important to create management guidelines, define strategies for optimizing energy production, and fill gaps in the species' production chain (Lima et al. 2023). Studies have stressed the potential of wood for bioenergy (Silva et al. 2021; Santos et al. 2024; Moraes et al. 2023). Studies that contribute to the carbon ecology of these forest plantations are important, especially for assessing carbon stocks on an annual basis. The species displays annual growth rings, making it possible to obtain the annual apparent density (12% moisture content) using X-ray densitometry (Moraes et al. 2023). Thus, an equation to predict basic density using the apparent density of growth rings would help quantify annual carbon stocks and improve predictions of community dynamics. Although there are general equations for converting apparent density at 12% moisture content to basic density (Reyes et al. 1992; Simpson 1993; Vieilledent et al. 2018), creating a specific equation for *T. vulgaris* plantations ensures greater accuracy of results. Given the above, this study aimed to (i) develop an equation to estimate the basic wood density from the apparent density of growth rings in *T. vulgaris* plantations in Amazonia, and (ii) apply the generated equation to estimate the mean and annual basic density along the stems and to evaluate the variation of these densities.

Developing a species-specific equation to predict basic density from apparent density is crucial, as general conversion models may not ensure the required accuracy. By providing reliable estimates of mean and annual basic density in *T. vulgaris* plantations in Amazonia, this study contributes to filling key gaps in the species' production chain, supports the quantification of carbon stocks, and advances strategies for sustainable energy production.

Materials and Methods

Characterization and History of the Study Area

The study was conducted on two pure *T. vulgaris* plantations, each measuring approximately 1.6 ha, located on the property of Jari Celulose S.A., in the Monte Dourado District, municipality of Almeirim, Pará, Brazil (Fig. 1a). The Köppen-Geiger classification for the region is type *Am* (Alvares et al. 2013). The average annual rainfall (data from the study area between 2010 and 2021) is 2145 mm, with a dry season between august and november, and an average annual temperature of 27.3 °C (Fig. 1b). It is worth mentioning that the air temperature data were obtained by the Monte Alegre (State of Pará, Brazil) weather station (a city near the study area) and made available by the National Institute of Meteorology (INMET 2023). One of the experimental plantations is located on a Yellow Oxisol with sandy loam texture (0° 47' 17.13" S and 52° 37' 8.32" W), and the other on a Yellow Oxisol with very clayey texture (0° 53' 29.30" S and 52° 29' 15.09" W) (Teixeira et al. 2023).

The plantations were established in 2010, with a spacing of 3 m x 2 m (6 m²) for both areas. Before the experiments were implemented, the areas were occupied by *Eucalyptus* sp. plantations. For site preparation, post-emergence manual chemical weeding was carried out, and soil acidity was corrected with lime over the entire area (1500 kg ha⁻¹) 30 days before planting the seedlings (Teixeira et al. 2023). The experiments were established using seeds from mother trees located in the municipalities of Almeirim, Belterra, and Santarém (State of Pará, Brazil) and Macapá (State of Amapá, Brazil).

Experimental Design and Sampling of *Tachigali vulgaris* Wood

The experiments were conducted using a randomized block design with a factorial scheme, comprising 4 blocks per area. The treatments consisted of 4 different phosphorus (P) doses and 3 different potassium (K) doses, which were combined with each other, totaling 12 treatments and 48 plots in each experimental area. Each plot had dimensions of 12 m x 14 m (168 m²), composed of 4 rows with 7 plants (28 plants/plot), from which the 6 central trees of each plot were considered as the net plot area. These plots were monitored annually to conduct research on growth and mortality rates, as detailed in the study by Teixeira et al. (2023).

The fertilizer used as the source of P was triple superphosphate (41% P₂O₅), and its application was carried out at the time of seedling planting, into the bottom of the planting pit. Potassium chloride was used as the source of K (58% K₂O), and

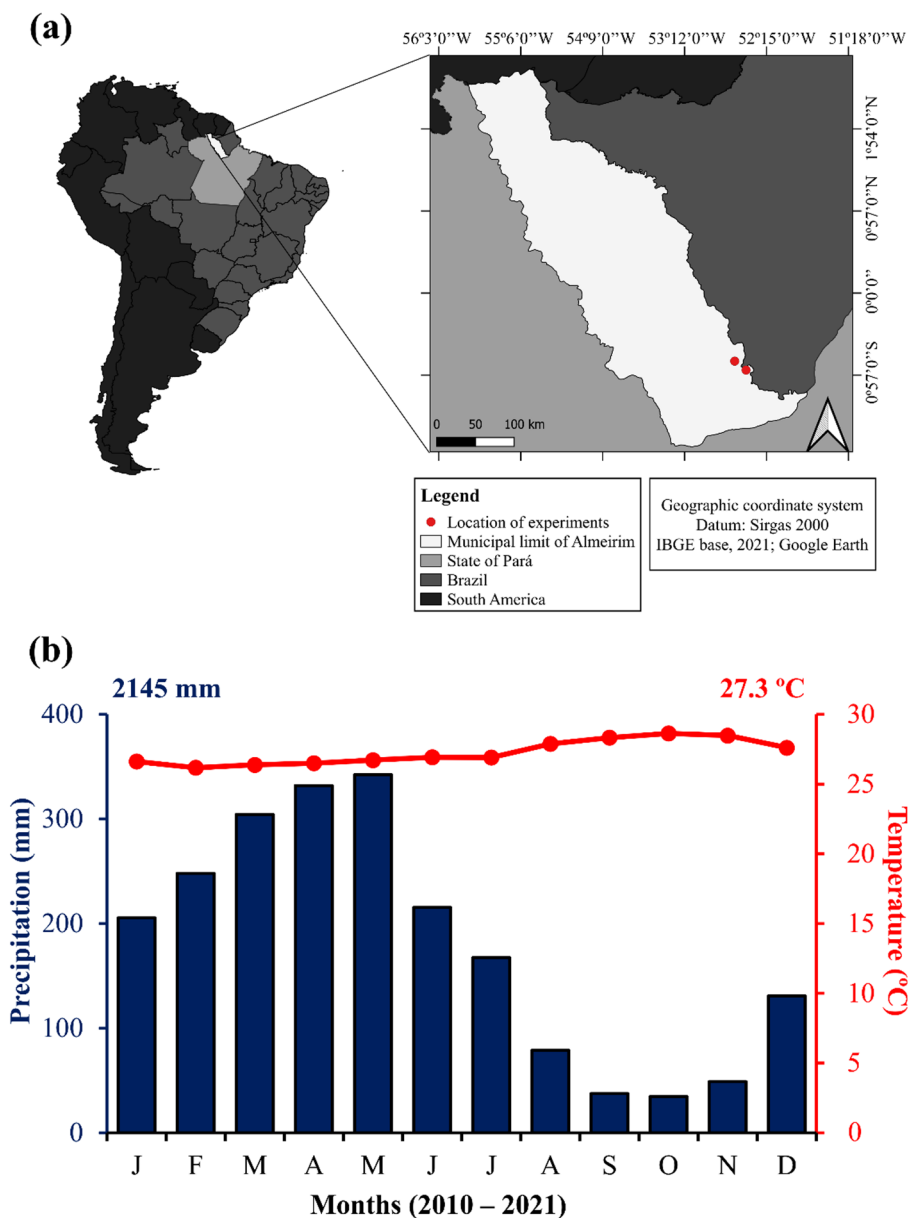


Fig. 1 Location of the study area, in the district of Monte Dourado, Almeirim, Pará, Brazil (a); climate chart for the study area (b)

its application was performed in split doses (40% at 20 days and 60% at 90 days after planting). Since *T. vulgaris* is a species capable of symbiotic association with nitrogen-fixing bacteria, only an initial nitrogen (N) application was carried out using ammonium sulfate fertilizer (21% N), 20 days after planting for all treatments. For the present study, sample trees were harvested from both plantations (Fig. 2a), and



Fig. 2 Experimental plantations of *T. vulgaris* evaluated on soils with sandy loam texture and very clayey texture (a), disk sampling along the stem of non-forked and forked trees (b), disks split in half generating duplicates with ≈ 2.5 cm thickness (c), basic density analysis (d), and X-ray densitometry analysis (e)

two contrasting treatments (among the 12 installed) were evaluated: without P and K fertilization (0P-0 K) and with the maximum P and K fertilization (320 kg ha⁻¹ of P₂O₅ and 199 kg ha⁻¹ of K₂O—780P-343 K). More detailed descriptions and information on the experimental plantations can be found in Teixeira et al. (2023).

In 2021, when 11 years old, 32 trees were sampled (16 trees in the sandy loam soil and 16 trees in the very clayey soil—0P-0 K and 780P-343 K), including 15 non-forked trees and 17 forked trees. The mean diameter at breast height (DBH) was 15.05 cm (± 3.54 cm) for the main stem and 10.24 cm (± 2.33 cm) for the secondary stem. Mean total height was 22.65 m (± 2.92 m), commercial height was 19.10 m (± 3.03 m), and tree volume without bark was 0.26 m³ (± 0.12 m³) (Table 1).

Discs approximately 5 cm thick were cut from the trees along the commercial height, considered up to the minimum diameter of 5 cm with bark. For non-forked

Table 1 Dendrometric information on the 32 *T. vulgaris* trees collected at 11 years of age in the two experimental areas in Monte Dourado, district of Almeirim, Pará, Brazil

Texture	Fertilization	Stem type	DBH main stem (cm)	DBH secondary stem (cm)	TH (m)	CH (m)	Vwb (m ³)	
Sandy loam	0P-0 K	Non-forked	18.71 (3.17)	–	25.76 (1.43)	22.40 (1.60)	0.34 (0.09)	
		Forked	15.34 (3.04)	10.60 (1.32)	24.10 (2.08)	21.08 (2.11)	0.33 (0.10)	
	780P-343 K	Non-forked	15.95 (6.15)	–	24.28 (1.42)	20.72 (2.26)	0.24 (0.16)	
		Forked	13.41 (3.20)	7.85 (1.72)	22.94 (2.09)	18.40 (3.32)	0.240 (0.11)	
	Very clayey	0P-0 K	Non-forked	13.53 (1.85)	–	21.53 (1.08)	17.67 (1.20)	0.16 (0.05)
			Forked	14.21 (3.21)	11.62 (2.78)	21.10 (3.02)	17.43 (3.83)	0.29 (0.18)
		780P-343 K	Non-forked	15.57 (2.19)	–	20.73 (4.11)	18.10 (1.87)	0.18 (0.04)
			Forked	13.54 (3.45)	10.58 (1.66)	20.88 (3.45)	17.01 (3.10)	0.26 (0.12)
Average			15.05 (3.54)	10.24 (2.33)	22.65 (2.92)	19.10 (3.03)	0.26 (0.12)	

DBH: Diameter at breast height; TH: Total height; CH: Commercial height; Vwb: Volume without bark. Average (standard deviation)

trees, discs were sampled at relative positions of 0%, diameter at breast height (DBH, measured at 1.30 m from the ground), 25, 50, 75, and 100%. The same sampling was also applied to forked trees, both for the main and secondary stems, with additional sampling performed at the base of the fork and at the beginning of the main stem (Fig. 2b). Subsequently, the discs were halved, generating duplicates approximately 2.5 cm thick (Fig. 2c). One of the discs was used for determining the basic wood density (Fig. 2d) and the other for X-ray densitometry (Fig. 2e).

Determination of Wood Basic Density

The basic density of wood wedges was determined following the NBR 11,941 standard (ABNT 2003). Sample saturated volume was obtained by water immersion, and dry mass was measured after oven-drying at 105 °C. At each sampling position along the stem, two opposing wedges were taken from the discs, except at the DBH position. In this study, the basic density values served as input for developing a density prediction model. Detailed analyses of basic density variation in relation to stem type, soil texture, and fertilization were previously reported by Santos et al. (2025).

Determination of Wood Apparent Density by X-ray Densitometry

For each disk sampled in different longitudinal positions, a cross-sectional radius with dimensions of approximately 1 cm wide x 2.5 cm thick x length equivalent to the collected radius of the disk was collected. The sampled radii were cut trans-

versally with a precision metallographic saw ISOMET® 5000 (Buehler, Lake Bluff, Illinois, USA) equipped with a diamond disk, after the samples were saturated to ensure the homogeneity of the thickness at the time of cutting. After the cuts, the rays had approximate dimensions of 1 cm wide x 1 mm thick x length equal to the chosen radius of the disc. The samples were stored in a conditioning chamber (20 °C and 60% relative humidity) to achieve a stable humidity of 12% (Tomazello et al. 2008).

To determine the apparent density by X-ray densitometry of the growth rings of *T. vulgaris*, the rays were initially radiographed in a Faxitron MX20-DC12 irradiation chamber (Faxitron X-Ray, Lincolnshire, Illinois, USA), together with a cellulose acetate wedge with known density to calibrate the density values. The equipment configuration was 5 s of irradiation and 30 kv of voltage. The radiographed images were analyzed using WinDendro Density 2017a® software (Regent Instruments Inc., Quebec, Canada), from which average apparent density values at 12% moisture content were obtained per growth ring of *T. vulgaris* trees. The growth rings of the species in forest plantations in the study region are annual and are delimited by thick-walled and radially flattened latewood fibers (commonly called fibrous zones), as reported by Moraes et al. (2023) and Ceretta et al. (2025).

In addition, among the 32 *T. vulgaris* trees evaluated, the disks collected at 0% of the commercial height generally presented 11 growth rings, corresponding to the planting age, which confirms the annuality of the species growth rings (Fig. 3). In three trees, however, only 7 (one tree) and 9 rings (two trees) were identified. This variation may be related to differences in radial growth or the difficulty of ring formation and visibility in the first years of development. For the other positions, between 7 and 11 rings (average=10 rings) were found for DBH, between 6 and 10 rings (average=9 rings) for 25% of the commercial height, between 5 and 9 rings (average=7 rings) for 50% of the commercial height, between 4 and 8 rings (average=6 rings) for 75% of the commercial height, and between 2 and 6 rings (average=4 rings) for 100% of the commercial height.

The apparent density of *T. vulgaris* discs was determined by the weighted mean of growth ring density according to the annual basal area increment (Eq. 1), as proposed by Hornink et al. (2025).

$$WDD_{WA} = \sum_{t=1}^n \frac{RD_{12\%t} * BAIt}{BA_t} \quad (1)$$

where: WDD_{WA} is the weighted average wood disc density (g cm^{-3}), $RD_{12\%t}$ is the average apparent density of the growth ring at 12% moisture formed in year t (g cm^{-3}), $BAIt$ is the basal area increment in year t (cm^2), and BA_t is the total basal area in year t (cm^2).

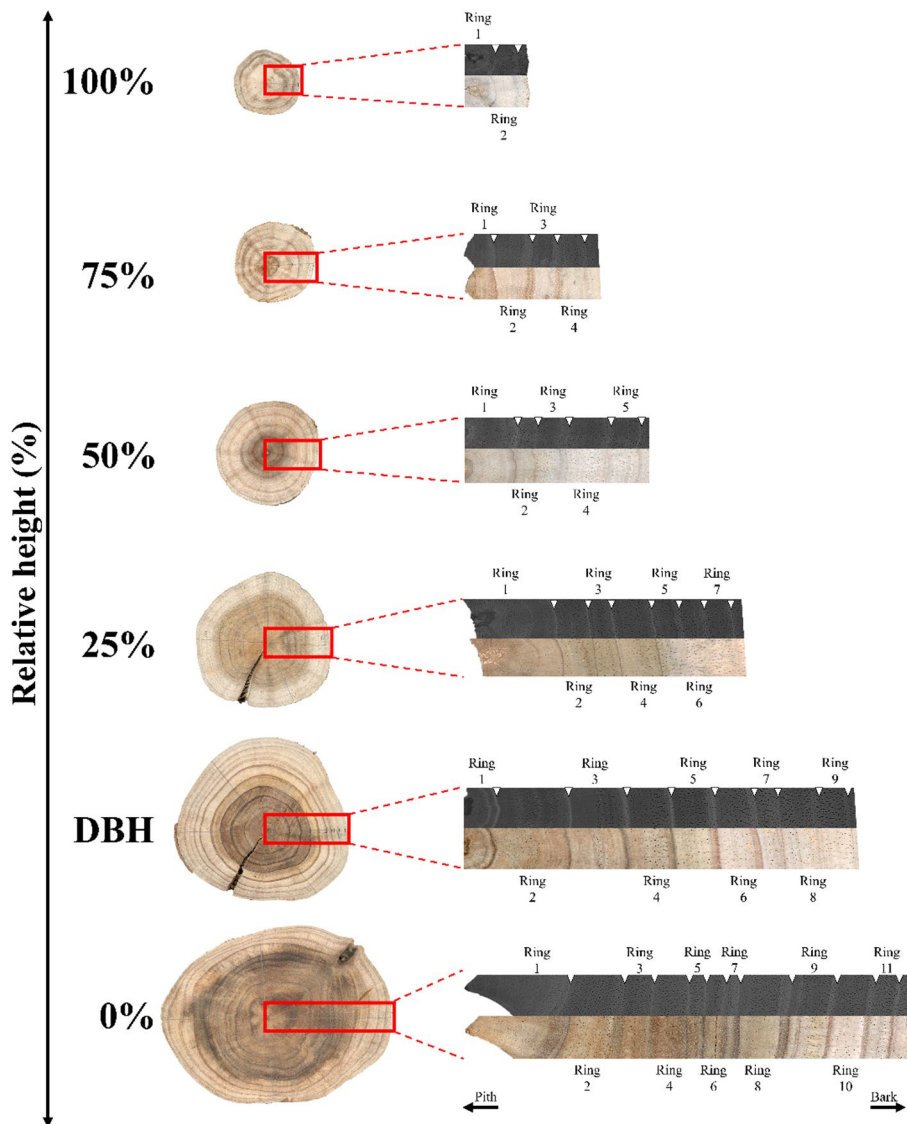


Fig. 3 Macroscopic and X-ray images of transverse sections, showing the boundaries of growth rings of *T. vulgaris* along the relative height of the tree (0%, DBH, 25%, 50%, 75%, and 100%)

Data Analysis and Statistics

Initially, density values (basic and apparent) were analyzed based on simple descriptive statistics. The mean of the trees (non-forked and forked) was calculated by the arithmetic mean of the discs along the stem, considering the positions of 0, 25, 50, 75, and 100%, in order to maintain the same pattern of positions among the stems. This study did not aim to evaluate wood density as a function of experimental factors.

This approach has already been explored for basic density in another study (Santos et al. 2025). However, density characterization was performed by differentiating between non-forked and forked trees, as it has been reported that the presence of forking reduces density in *T. vulgaris* trees (Barros-Junior et al. 2022; Lima et al. 2023; Moraes et al. 2023).

Basic density and apparent density values obtained from the same discs along the longitudinal section of the stem were used to fit statistical models aimed at predicting wood basic density as a function of apparent density and factors associated with management (fertilization), site conditions (soil textural class), and tree morphological characteristics (absence or presence of forking). To this end, a linear mixed-effects modeling approach was adopted in order to simultaneously account for fixed effects and the hierarchical structure of the data.

Basic density was defined as the response variable. In the full model, fixed effects included apparent density (continuous variable) and, as categorical variables (dummy variables), fertilization (absence of P and K; presence of P and K), soil textural class (sandy loam and very clayey), and the absence or presence of forking (non-forked and forked). To evaluate whether these factors contributed significantly to the prediction of basic density beyond the effect of apparent density, a reduced model containing only apparent density as a fixed effect was fitted. In both models, random effects were included in the intercept, accounting for the dependency structure of the data, with trees nested within experimental blocks, in order to capture potential unexplained variability associated with these sampling units. The models were fitted using the maximum likelihood method and compared using the likelihood ratio test, adopting a significance level of 5% to assess whether the inclusion of these factors resulted in a significant improvement in model fit.

The quality of model fit and the predictive performance of the final model were evaluated using different complementary statistics: (i) the Pearson correlation ($r_{y\hat{y}}$) between observed and estimated basic density values, used as a descriptive measure of the degree of linear association between model-predicted values and observed data (Eq. 2); (ii) the marginal coefficient of determination, referred to in this study simply as the coefficient of determination (R^2), which expresses the proportion of variance explained by the fixed effects (Eq. 3); (iii) the root mean square error (RMSE%) (Eq. 4) and (iv) the mean absolute error (MAE%) (Eq. 5), used to quantify the magnitude of prediction errors. The processing was performed in R software (version 4.2.3), with the *nlme* package (Linear and Nonlinear Mixed Effects Models. R package version 3.1–162) (R Development Core Team 2023).

$$r_{y\hat{y}} = \frac{\sum_{i=1}^n (Y_i - \bar{Y}) * (\hat{Y}_i - \bar{\hat{Y}})}{\sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2 * (\hat{Y}_i - \bar{\hat{Y}})^2}} \quad (2)$$

$$R^2 = 1 - \frac{RSS}{TSS} * 100 \quad (3)$$

$$RMSE (\%) = \frac{100}{\bar{Y}} \sqrt{\frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{n}} \quad (4)$$

$$MAE (\%) = \frac{1}{n} \sum_{i=1}^n \left(\frac{|Y_i - \hat{Y}_i|}{|\bar{Y}|} \right) * 100 \quad (5)$$

where: r_{yy} is the Pearson correlation between observed and estimated values; Y_i are the observed values; $\hat{Y}_i$ are the estimated values; $\bar{Y}$ average of observed values; $\bar{\hat{Y}}$ average of estimated values; n is the number of observations; R^2 is the coefficient of determination; RSS is the residual sum of squares; TSS is the total sum of squares; RMSE is the root mean square error (%); MAE is the mean absolute error (%); $|Y_i - \hat{Y}_i|$ is the absolute error for each observation; $|\bar{Y}|$ is the mean of the observed absolute values.

To validate the equation adjustment, the database was randomly divided into two sets: calibration (70% of the data) and validation (30% of the data). For the separate calibration data set, the nested mixed model comparison approach was used, as previously described. The model obtained was applied to the validation data set, thus obtaining observed and estimated values that were compared using simple linear regression and obtaining the statistics r_{yy} , R^2 , RMSE%, and MAE%.

Furthermore, the weighted average values of the experimentally obtained trees were compared with the values found by the equation and the percentage difference (%) was calculated to verify the overestimation or underestimation for each evaluated tree (Eq. 6).

$$Difference (\%) = \frac{(WBD_{equation} - WBD_{WIM})}{WBD_{WIM}} \times 100 \quad (6)$$

where: $WBD_{equation}$ is the wood basic density value obtained from the conversion of the apparent density at 12% humidity by the population equation ($g\ cm^{-3}$), WBD_{WIM} is the wood basic density value obtained by the immersion method ($g\ cm^{-3}$).

Subsequently, the density values (for each sampled disc and for the average of the trees) obtained by the immersion method and the population equation were classified as low density ($<0.500\ g\ cm^{-3}$) and medium density ($\geq 0.500\ g\ cm^{-3}$) as adopted by Barros-Junior et al. (2022), (Moraes et al. 2023), Santos et al. (2025).

Finally, the annual basic density was determined for all sampled positions of *T. vulgaris* trees from the generated equation. Subsequently, the average annual values were evaluated for each position within the stem and the density was classified (low or medium) per year. It is important to note that, although the basic density of the wood at the DBH position was not determined directly, the apparent density values of the growth rings at that position were obtained. After developing the conversion equation between apparent density and basic density (based on other positions), this

equation was then applied to the DBH growth rings to estimate the corresponding basic density.

Results

Characterization of the Apparent and Basic Density of *T. vulgaris* Trees

The overall average apparent density was 0.599 g cm^{-3} ($\pm 0.057 \text{ g cm}^{-3}$), with values for non-forked trees of 0.613 g cm^{-3} ($\pm 0.060 \text{ g cm}^{-3}$) and forked trees of 0.587 g cm^{-3} ($\pm 0.054 \text{ g cm}^{-3}$), ranging from 0.495 g cm^{-3} to 0.723 g cm^{-3} (Fig. 4a). For basic density, the overall mean was 0.507 g cm^{-3} ($\pm 0.045 \text{ g cm}^{-3}$), with basic density for non-forked trees of 0.517 g cm^{-3} ($\pm 0.045 \text{ g cm}^{-3}$) and forked trees of 0.498 g cm^{-3} ($\pm 0.045 \text{ g cm}^{-3}$), ranging from 0.419 g cm^{-3} to 0.596 g cm^{-3} (Fig. 4a).

The same pattern of longitudinal variation was observed for non-forked and forked trees in both density forms evaluated (Fig. 4b and c). The highest average density values were found at the base, with a considerable reduction in density at the relative position of 25%. This reduction for non-forked trees was 0.153 g cm^{-3} (21%) and 0.159 g cm^{-3} (25%) for apparent and basic density, respectively. For forked trees there was a reduction of 0.200 g cm^{-3} (27%) and 0.181 g cm^{-3} (29%) for apparent and basic density, respectively. In general, from the relative height of 50% onward, there was a tendency for density to increase toward the top (100% of the commercial height) for both densities evaluated.

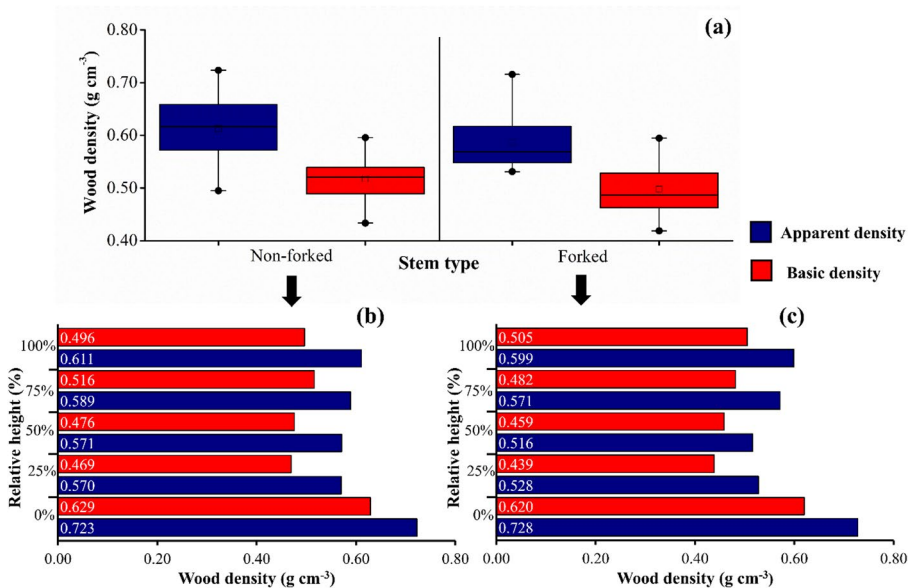


Fig. 4 Average apparent and basic density (a) and longitudinal variation (b and c) of non-forked and forked trees of *T. vulgaris*

Table 2 Studies on the density of *T. vulgaris* wood carried out over the last 40 years

Age (years)	Tested factor	Density (g cm ⁻³)		References
		Basic	Ap-parent (12%)	
11.0	Fertilization, soil texture and forking	0.507	0.599	Current study
8.5	Spacing and forking	0.529	0.674	Moraes et al. (2023)
7.25	Spacing and forking	0.441–0.594	–	Lima et al. (2023)
8.5		0.486–0.597	–	
7.25	Spacing and forking	0.443–0.529	–	Barros-Junior et al. (2022)
7.25	Spacing	0.493	–	Silva et al. (2021)
5.8	Spacing	0.564–0.687	–	Tonini et al. (2018)
20.0	Diametric class	0.581	–	Orellana et al. (2018)
15.0		0.562	–	
8.0		0.633	–	
	–			Tomaselli et al. (1983)

Table 3 Models were adjusted using the maximum likelihood method and compared using the likelihood ratio test, at a 5% significance level, to verify whether the experimental variables influence the prediction of basic density

Model	df	AIC	BIC	LogLik	Test	L.Ratio	p-value
Reduced model = WBD ~ WAD	5	–	–	298.8642			
		587.728	571.573				
Complete model = WBD ~ WAD + fertilization + soil texture + Stem type	8	–	–	301.3911	1 vs. 2	5.053888	0.1679 ^{ns}
		586.782	560.933				

WBD: Wood basic density; WAD: Wood apparent density; fertilization: Absence or presence of phosphorus and potassium fertilization; soil texture: Sandy loam texture and very clayey texture; stem type: Absence or presence of forking; df: Degrees of freedom; AIC: Akaike information criterion; BIC: Bayesian Information Criterion; LogLik: Log-likelihood; L.Ratio: Likelihood ratio; ns: Not significant at the 5% significance level

The literature of the last 40 years for *T. vulgaris* presents a significant variation in the basic density of *T. vulgaris* wood, mainly depending on age, silvicultural treatments (e.g., planting spacing) and biome (Table 2). Even with considerable variability reported in the literature, the values observed in these studies are generally similar to those found. Furthermore, it is noteworthy that only one study in the literature presents apparent density values for the species.

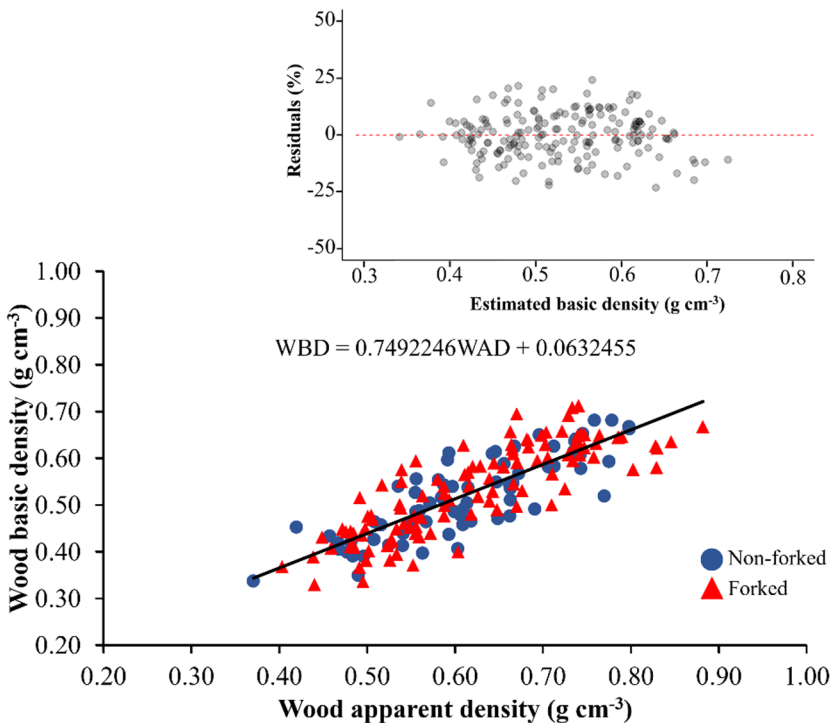
Basic Density Estimation from Apparent Density

The variables stem type, soil texture, and fertilization did not affect the relationship between apparent density and basic density of wood for *T. vulgaris* trees ($p > 0.05$; Table 3).

Table 4 Statistics from the simple linear regression model adjusted by the maximum likelihood method and quality statistics for population equations (full dataset and validation dataset) for *T. vulgaris* trees

Model: $WBD = 0.7492246WAD + 0.0632455$				
Coefficients:	Std.Error	df	t-value	p-value
Intercept	0.0221	154	2.86808	0.0047*
WAD	0.035	154	21.4058	0.0000*
Quality statistics				
	r_{yy}	R^2	RMSE%	MAE%
Population equation (full dataset)	0.84	0.71	9.31	7.28
Population equation (validation dataset)	0.80	0.64	9.59	7.15

WBD: Wood basic density; WAD: Wood apparent density; Std.Error: Standard error; df: Degrees of freedom; r_{yy} : Pearson correlation; R^2 : Coefficient of determination; RMSE%: Root mean square error; MAE%: Mean absolute error; *: significant at the 5% significance level

**Fig. 5** Simple linear regression model fitted by the maximum likelihood method between apparent and basic density, with residuals of the fitted model for *T. vulgaris* trees. WBD: wood basic density, WAD: wood apparent density

Thus, the model using only apparent density as an explanatory variable was used, generating the population equation ($WBD = 0.7492246WAD + 0.0632455$) for the species (Table 4; Fig. 5). The linear regression model relating basic density and appar-

ent density was significant ($p < 0.001$), presenting Pearson correlation ($r_{yy} = 0.84$), coefficient of determination ($R^2 = 0.71$), root mean square error (RMSE%) = 9.31, and mean absolute error (MAE%) = 7.28 (Table 4). The validation of the adjustment of the equations presented quality statistics similar to those obtained for the population equation, demonstrating the consistency of the adjusted models and their suitability for reliable estimates. Furthermore, the residuals (%) show a random distribution along the fitted values, indicating that the generated regression model presents an adequate relationship between basic density and apparent density (Fig. 5).

Table 5 Average wood basic density values for the 32 *T. vulgaris* trees evaluated in the study obtained by the immersion method, population equation and the difference between the averages for each tree in percentage

Trees	Forking	WBD _{WIM}	WBD _{equation}	Difference (%)*
1	Non-Forked	0.536	0.557	3.99%
2	Non-Forked	0.596	0.605	1.62%
3	Non-Forked	0.582	0.573	- 1.50%
4	Non-Forked	0.506	0.505	- 0.16%
5	Non-Forked	0.480	0.478	- 0.38%
6	Non-Forked	0.433	0.434	0.14%
7	Non-Forked	0.489	0.539	10.34%
8	Non-Forked	0.494	0.492	- 0.52%
9	Non-Forked	0.507	0.525	3.57%
10	Non-Forked	0.539	0.525	- 2.63%
11	Non-Forked	0.450	0.459	1.95%
12	Non-Forked	0.537	0.557	3.61%
13	Non-Forked	0.528	0.543	2.94%
14	Non-Forked	0.521	0.503	- 3.50%
15	Non-Forked	0.563	0.541	- 4.04%
Average		0.517 (0.045)	0.522 (0.045)	1.03% (3.65%)
16	Forked	0.530	0.559	5.52%
17	Forked	0.528	0.509	- 3.61%
18	Forked	0.462	0.468	1.22%
19	Forked	0.457	0.466	1.96%
20	Forked	0.501	0.504	0.65%
21	Forked	0.477	0.462	- 3.13%
22	Forked	0.594	0.599	0.83%
23	Forked	0.473	0.489	3.54%
24	Forked	0.462	0.489	5.75%
25	Forked	0.462	0.474	2.60%
26	Forked	0.526	0.526	- 0.13%
27	Forked	0.471	0.492	4.41%
28	Forked	0.487	0.481	- 1.10%
29	Forked	0.516	0.461	- 10.68%
30	Forked	0.561	0.533	- 4.99%
31	Forked	0.419	0.474	13.29%
Average		0.498 (0.045)	0.503 (0.040)	1.15% (5.23%)
Overall average		0.507 (0.045)	0.512 (0.043)	1.09% (4.48%)

WBD_{WIM}: Wood basic density obtained by the immersion method; WBD_{equation}: Wood basic density obtained by population equation. Average (standard deviation)

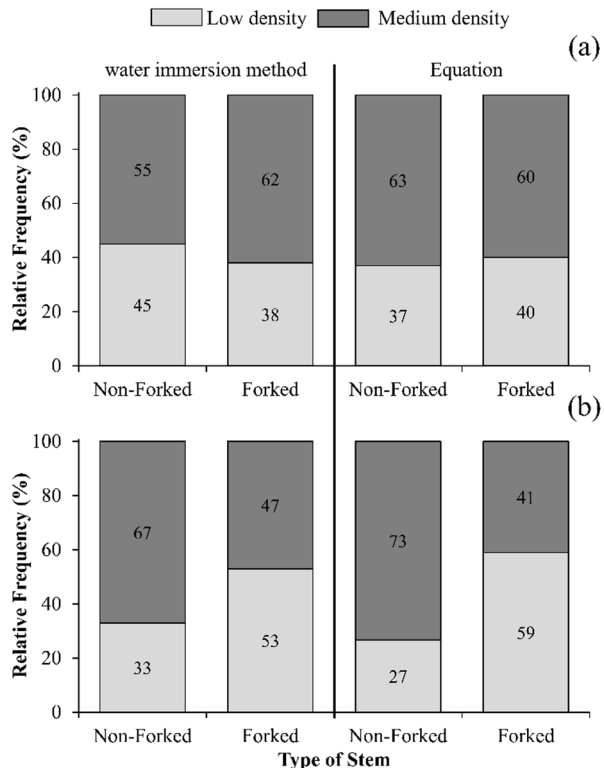
* A positive difference indicates that the equation overestimated the values, and a negative difference indicates that the equation underestimated the values

The population equation obtained was applied to the average basic density values of *T. vulgaris* trees (Table 5). The general average basic density obtained by the population equation was 0.512 g cm^{-3} ($\pm 0.043 \text{ g cm}^{-3}$), with an overestimation of the real average value of 0.005 g cm^{-3} ($1.09\% \pm 4.48\%$). Among the 32 *T. vulgaris* trees evaluated, the population equation underestimated by up to 10.68% and overestimated by up to 13.29% (Table 5).

Classification of the Average Basic and Annual Density of *T. vulgaris* Trees from the Population Equation

To classify the basic density of the discs, the discs at the base of the bifurcation and the beginning of the main stem for bifurcated trees were considered (see Fig. 2), as these positions were used in the development of the equation. The non-forked trees (75 discs evaluated) presented 55% of the discs classified as medium density ($\geq 0.500 \text{ g cm}^{-3}$). In general, this result had a great influence from the base of the trees, in which all the discs (15 discs) showed basic density $> 0.500 \text{ g cm}^{-3}$. Furthermore, the 75% relative height showed 10 discs (out of 15 evaluated) with basic density $> 0.500 \text{ g cm}^{-3}$ (Fig. 6a). For the forked trees (112 discs evaluated), 62% of the discs were classified as medium density ($\geq 0.500 \text{ g cm}^{-3}$), this result being due to the discs at the base, base of the bifurcation and the beginning of the main stem that presented basic density $> 0.500 \text{ g cm}^{-3}$ (Fig. 6a). When comparing the percentage

Fig. 6 Comparison of the relative frequency of basic density classified as low density ($< 0.500 \text{ g cm}^{-3}$) and medium density ($\geq 0.500 \text{ g cm}^{-3}$) between the water immersion method and the population equation for the discs sampled for the different positions within the stem (a) and for the average density of the trees (b). Basic density classification adopted by Barros-Junior et al. (2022), Moraes et al. (2023), and Santos et al. (2025)



obtained by the immersion method with that obtained by the equation, for the non-forked trees, 8% more of the sampled discs (6 discs) were considered as having an average density by the equation, while, for the forked trees, 2% less of the sampled discs (2 discs) were considered as having an average density.

For the average WBD, 67% of the non-forked trees (10 trees) were classified as medium density. For forked trees (9 trees) the largest proportion (53%) has low density ($<0.500 \text{ g cm}^{-3}$, Fig. 6b). When comparing the difference between the percentage obtained by the immersion method with that obtained by the equation, for the non-forked trees, one tree (6%) was classified as medium density (Fig. 6b). For forked trees, one less tree (2%) was classified as low density (Fig. 6b).

After applying the population equation to the growth rings of *T. vulgaris* trees, it was possible to verify the behavior of the average basic density throughout the cambial age for the sampled heights (Fig. 7). The base of the trees (0% of the relative height) showed a more significant increase in density until the 3rd year, followed by a tendency for stabilization of the average basic density values from the 4th year

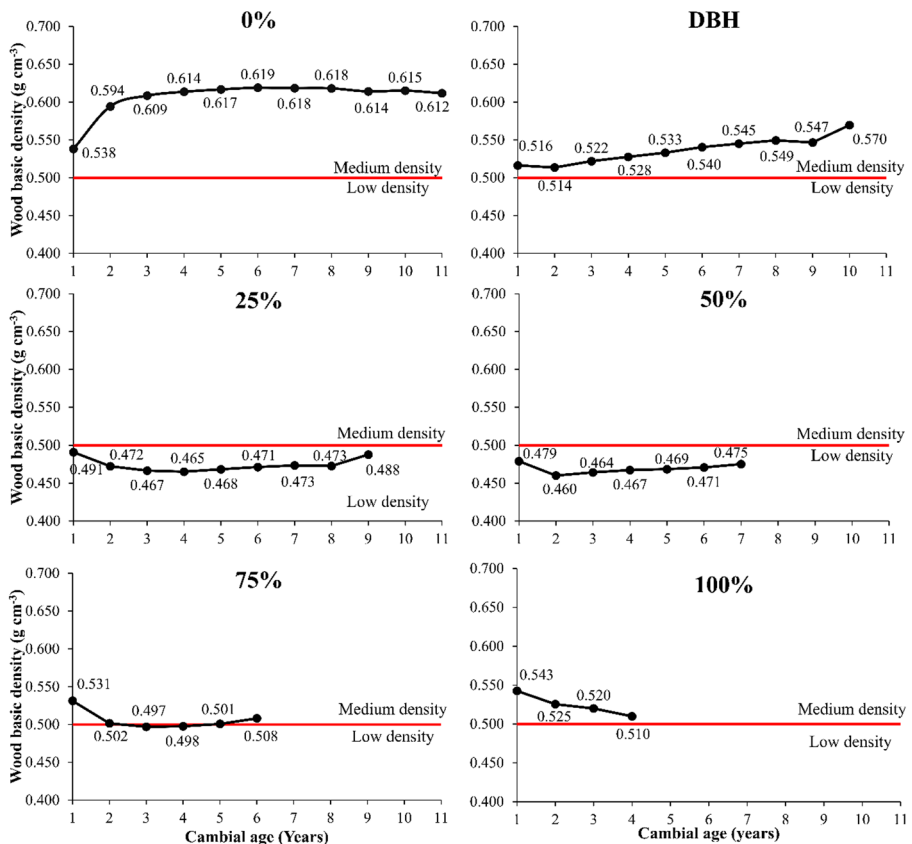


Fig. 7 Average basic density values obtained by the population equation over the cambial ages in the different relative positions of the *T. vulgaris* trees. The red lines represent the classification range in low density ($<0.500 \text{ g cm}^{-3}$) and medium density ($\geq 0.500 \text{ g cm}^{-3}$). Basic density classification adopted by Barros-Junior et al. (2022), Moraes et al. (2023), and Santos et al. (2025)

Table 6 Variation of estimated basic density in the radial direction, considering different relative positions of commercial height in *T. vulgaris* trees

Height relative (%)	Basic density (g cm^{-3})			CV (%)
	Average	Minimum	Maximum	
0%	0.606 (0.056)	0.417	0.767	9.17
DBH	0.536 (0.056)	0.362	0.644	10.41
25%	0.475 (0.056)	0.320	0.632	11.84
50%	0.472 (0.060)	0.375	0.646	12.64
75%	0.507 (0.060)	0.392	0.684	11.75
100%	0.526 (0.053)	0.414	0.641	10.04

CV: Coefficient of variation.

Average (standard deviation)

until the 11th year (between 0.609 and 0.618 g cm^{-3}) and an average of 0.606 g cm^{-3} ($\pm 0.056 \text{ g cm}^{-3}$) (Table 6). For DBH, there was generally an increase until the 11th year, with a variation between 0.516 and 0.570 g cm^{-3} and an average of 0.536 g cm^{-3} ($\pm 0.056 \text{ g cm}^{-3}$).

The heights of 25% and 50% showed a tendency for density stability over the years, with averages of 0.475 g cm^{-3} ($\pm 0.056 \text{ g cm}^{-3}$) and 0.472 g cm^{-3} ($\pm 0.060 \text{ g cm}^{-3}$), respectively (Table 6). The two heights presented density values classified as low density for all growth rings (Fig. 7). For the relative heights of 75% and 100%, there was a reduction until the 4th year, and subsequently, the height of 75% showed a tendency for an increase in basic density, with an average of 0.507 g cm^{-3} ($\pm 0.060 \text{ g cm}^{-3}$), with the 3rd and 4th years being classified as low density. For the height of 100% (average = $0.526 \pm 0.053 \text{ g cm}^{-3}$), all growth rings were classified as medium density (Fig. 7). The variation in growth ring density along the heights ranged from 0.320 – 0.767 g cm^{-3} (Table 6).

The classification of annual basic density for the different positions sampled along the stem showed that the discs at the base had the highest number of growth rings with medium density. Only in the first year was there a higher percentage of low density (32%) for this position, with an abrupt decrease in this percentage already in the second year (3%). From the sixth year onwards, 100% of the growth rings showed medium density (Fig. 8). In general, there was an increase in the proportion of growth rings with medium density with the increase in cambial age at DBH, reaching the tenth year with 95% of the rings classified as medium density. For the 25% and 50% positions, the highest proportion was of low density for all years evaluated (Fig. 8). The growth rings from the 75% position showed an increase in low-density rings from the first to the fourth year, followed by an increase in the proportion of medium-density rings in the fifth and sixth years. For the 100% position, there was a tendency for an increase in low-density rings with the increase in cambial age (Fig. 8).

Discussion

The main objective of this study was to develop a population equation to convert the apparent density (12% moisture) of *T. vulgaris* growth rings into basic density. The results showed that the equation had satisfactory statistical quality and produced estimates consistent with the immersion method. The analysis also showed the annual variation in density, the distribution between low ($< 0.500 \text{ g cm}^{-3}$) and medium density ($\geq 0.500 \text{ g cm}^{-3}$) classes, as well as the predominance of medium density in the

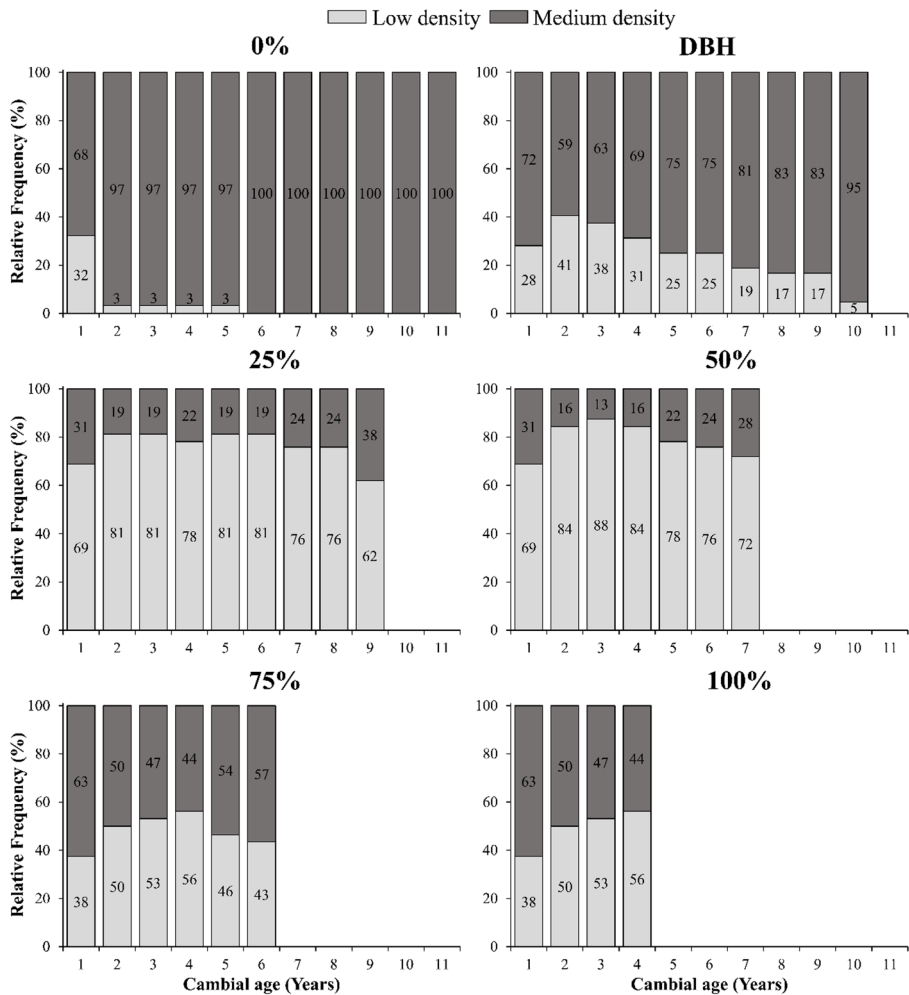


Fig. 8 Relative frequency of basic density obtained by the population equation classified as low density ($<0.500 \text{ g cm}^{-3}$) and medium density ($\geq 0.500 \text{ g cm}^{-3}$) throughout the cambial ages in the different relative positions of the *T. vulgaris* trees. Basic density classification adopted by Barros-Junior et al. (2022), Moraes et al. (2023), and Santos et al. (2025)

following regions of the tree: 0%, DBH, base of the fork and at the beginning of the main stem, presenting greater potential for energy purposes.

Characterization of the Apparent and Basic Density of *T. vulgaris* Trees

The lower values of basic density in relation to apparent density occur because basic density is calculated from the dry mass and the saturated volume of the wood, therefore always being lower than apparent density. The species' characteristic of presenting low to medium density is related to its ecological group (pioneer) that invests in rapid growth and, consequently, lower wood densities (Larjavaara and Muller-

Landau 2010; Williamson and Wiemann 2010). *T. vulgaris* presents high efficiency in the use of nutrients and resources with high photochemical performance and photosynthetic capacity, which results in rapid growth (Guimarães et al. 2018).

It has been reported that the presence of forking reduces density in *T. vulgaris* trees (Barros-Junior et al. 2022; Lima et al. 2023; Moraes et al. 2023). In general, the lower density observed in forked trees is associated with their smaller diameters (Table 1), since diameter directly influences the density of *T. vulgaris* (Santos et al. 2025). This may occur because the species is prone to competition for resources such as water, nutrients, and light (Ramos et al. 2021). With the low availability of these resources and the presence of a second stem, cell wall formation and expansion may become less efficient, resulting in a thinner cell wall, which decreases wood density (Barros-Junior et al. 2022). It is important to highlight that genetic factors, as well as genotype x environment interactions, can influence the diameter growth of *T. vulgaris* trees (Silva et al. 2021; Leão et al. 2023; Lima et al. 2023) and consequently affect density. In addition, it has been found that forking can lead to greater heterogeneity in wood density along the stem (Moraes et al. 2023), which is a disadvantage for energy purposes (Lima et al. 2023).

The reduction in basic density along the longitudinal direction up to the mean height of the trees, followed by an increase towards the top (Fig. 4), was also observed in *T. vulgaris* by Barros-Junior et al. (2022) and Moraes et al. (2023), at 87 and 102 months of age, respectively. This same behavior was reported for the *Eucalyptus*, *Corymbia* (Melo et al. 2024) and *Pinus taeda* (Neto et al. 2024) species. The lower density in these regions is likely associated with smaller diameters, resulting from their younger cambial age. With advancing age, changes occur in characteristics such as fiber length, cell wall thickness and fraction, fiber wall-to-lumen ratio, and tangential vessel diameter, among others (Palermo et al. 2015; Liu et al. 2020), which directly influence wood density.

Basic Density Estimation from Apparent Density

Basic density is strongly related to density and can be estimated by linear regression models (Reyes et al. 1992; Vieilledent et al. 2018). In the literature, it is reported that models for estimating basic tree density become more accurate by including the density and width of growth rings (Dahlen et al. 2018; Ortega Rodriguez and Tomazello-Filho 2019). For basic density, the method of determination using opposite wedges can represent the density variation from pith to bark; that is, the value obtained for each wedge reflects an average value of the growth ring variation. For apparent density, the average of the discs was obtained based on the basal area occupied by the sample (Eq. 1), thus also taking into account the variation of the growth rings.

The categorical variables (presence or absence of fertilization, soil texture, and presence or absence of forking) did not show influence on the prediction of basic density. This is probably related to the strong influence of genetic variability on the anatomical and physical characteristics of the species' wood (Silva et al. 2021). Leão et al. (2023) evaluated the genetic variability of *T. vulgaris* based on morphophysiological traits of wild seeds from the Amazonia region and found that genetic factors predominantly influence phenotypic variability. In addition, genotype x environment

interactions also affect the species' characteristics (Lima et al. 2023). Therefore, it is possible that, due to the use of wild seeds from different matrices (trees) for plantation formation, the genetic factor, combined with the different responses of each individual to the environment, was superior to the experimental factors evaluated.

Furthermore, the fact that fertilization did not influence density, unlike what was observed for other fast-growing species such as *Pinus* (Love-Myers et al. 2009; Ortega Rodriguez and Tomazello-Filho 2019) and *Eucalyptus* (Chambi-Legoas et al. 2021), may be related to the species' adaptability to Amazonian soils, which naturally have low natural fertility and high aluminum concentration (Santos et al. 2018). As a result, trees absorb a smaller amount of nutrients due to the high aluminum concentrations.

In general, Teixeira et al. (2023), when evaluating the effects of different doses of fertilization with P and K on dendrometric variables in the same experimental areas, that is, in sandy loam and very clayey textured soils, found low nutritional requirements for the species, as well as little or no response of the evaluated variables to the types of soil texture. The authors attributed this to one or more related factors, namely: the species' adaptation to low fertility soils; the high aluminum content in the soil; and the great genetic variability of the species, which, associated with environmental variations, caused each tree to present distinct phenotypic characteristics.

The absence of the bifurcation effect on the prediction of basic density, even though its presence has already been found to reduce density (Barros-Junior et al. 2022), may be related to the fact that this reduction is mainly observed for average tree values. However, when considering different positions of the stem, the main influence of bifurcation on density reduction occurs in regions between 25% and 50% (Fig. 4c). Meanwhile, regions below the forking and near the top show higher densities, similar to non-forked trees. Thus, it is likely that, because the density values of the discs were used to create the population equation, the influence of forking was not significant.

Moreover, other variables not considered in this study may influence the prediction of basic density. For example, Rocha et al. (2020), aiming to estimate basic density for four different *Eucalyptus* clones, found that for each clone, different climatic variables influenced the basic density estimate. Additionally, the effect of planting spacing may influence this estimate, as it has already been found that larger spacings generally increase the wood density of *T. vulgaris* trees (Barros-Junior et al. 2022; Moraes et al. 2023).

The good parameters of statistical quality (Table 4) and the similarity with average values of basic density observed in the literature for *T. vulgaris* (Table 2) indicate that the population equation is suitable for estimating basic density from apparent density. Thus, the generated equation can be suggested for *T. vulgaris* plantations under conditions similar to the study, that is, with maximum fertilization doses of 320 kg ha⁻¹ of P₂O₅, 199 kg ha⁻¹ of K₂O, and 21 kg ha⁻¹ of N; in yellow Latosol with sandy loam or very clayey texture; non-forked or forked trees; and plantations up to 11 years old.

Classification of the Average Basic and Annual Density of *T. vulgaris* Trees from the Population Equation

Based on the generated population equation, trees that present apparent density (12% moisture) above 0.583 g cm^{-3} probably present basic density $>0.500 \text{ g cm}^{-3}$. The classification of basic density showed that the discs from different positions of forked trees present a higher proportion of medium density than non-forked trees. This can be attributed to the greater number of samples considered for classification by discs, since forked trees took into account the discs from the base of the forked and the beginning of the main stem (Fig. 2), and these discs presented medium density influencing the proportion (Fig. 6a). However, for average values per tree, non-forked individuals present a higher proportion of medium density compared to forked trees (Fig. 6b). The average values of the trees were similar to those obtained by the classification carried out by Barros-Junior et al. (2022) and Moraes et al. (2023).

The increase in density observed over the years (more evident at the DBH position) is related to the fact that the species is fast-growing both in height and diameter, this is because it is a light-demanding species. However, this initial growth occurs with lower density wood, an adaptive strategy that favors rapid establishment over structural resistance. Only after stabilizing in the canopy do these trees redirect their resources to diameter growth to correct structural imbalance, promoting higher density wood (Williamson and Wiemann 2010; Ramanantoandro et al. 2016). The increase in density throughout the cambial age may be related to anatomical modifications, such as greater thickness and fraction of the fiber cell wall and smallest vessel diameter, as well as to the increase in the proportion of latewood, which exerts a great influence on the density of the growth rings (Guller et al. 2012; Palermo et al. 2015; Akello et al. 2024).

The classification of basic density by year (Fig. 8) corroborates the average values found (Fig. 7; Table 6), showing that the highest proportion of low-density wood occurs in regions of medium tree height (25% and 50%). In addition, this classification shows that from 5 to 6 years, the evaluated trees, in general, present better proportions of medium density. Studies conducted by Soares et al. (2022) in the fertilization experiment and in the spacing experiment with *T. vulgaris* in the same region found that the probable rotation age based on the point of maximum mean increment is between 5 and 6 years. Thus, from 7 to 8 years of planting, it is possible to carry out the rotation of the species with adequate density for the production of charcoal with better qualities. However, this indication is limited to regions closer to the base, as they present higher proportions of medium density.

The classification of density in the base-to-top direction is important, as it helps in the better indication of the wood (Moraes et al. 2023). Woods with basic density higher than 0.500 g cm^{-3} generate higher quality charcoal and increase productivity in masonry kilns, being the most recommended for steelmaking (Protásio et al. 2021). The potential of *T. vulgaris* for charcoal production has already been verified in the literature (Silva et al. 2021) and, thus, for better allocation of the produced charcoal, we suggest classifying the logs from the trees, since the density variation is large in the longitudinal direction. A study with wood residues from forest management in the Amazonia shows that separating species with similar wood properties

(e.g., basic wood density) for carbonization can produce more homogeneous charcoal and more suitable for different destinations such as steelmaking and domestic use (Lima et al. 2020).

Practical Implications and Limitations of the Research

The results obtained in this study provide unprecedented contributions to advances in research with *T. vulgaris* in the Amazonia. The population equation generated in the study can bring significant contributions to the study of the species' carbon stock, especially when evaluating the annual stock. We emphasize that the population equation was generated from the basic and apparent density values of the discs; therefore, applying it to growth ring density values may generate some uncertainties. The application of the X-ray densitometry technique makes it possible to obtain the apparent density values of growth rings relatively quickly and with high precision; however, determining the basic density for growth rings proves to be a difficult and time-consuming task. Thus, using values from the discs at different positions on the stem of *T. vulgaris* trees proved to be the most efficient way to capture density variations within the trees.

Future studies may include other variables in the equation, such as volumetric shrinkage coefficient and fiber saturation point (Vieilledent et al. 2018). Furthermore, should consider a larger moisture gradient in the database, allowing density conversion for any moisture content, as already done for *Eucalyptus grandis* (Costa et al. 2014). Finally, we recommend a larger sample, aiming to improve the equation's adjustment parameters, consequently, lower error embedded in the model.

Conclusions

The population equation ($WBD = 0.7492246WAD + 0.0632455$) generated overestimated by an average of 1.09% in relation to the actual values of basic density. 67% of non-forked trees and 47% of forked trees presented medium density ($\geq 0.500 \text{ g cm}^{-3}$). The study suggests that different regions of the tree can be allocated for different bio-energetic uses. Finally, the population equation generated to estimate basic density from apparent density at 12% moisture proved to be accurate, being recommended for plantations carried out under the same conditions.

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Data Availability Datasets that support the conclusions are included in the manuscript. In addition, the datasets analyzed in this research are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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