Fiber quality and wood basic density of species of the Savannah for productive purposes

Qualidade da fibra e densidade básica da madeira de espécies do Cerrado para fins produtivos

Calidad de la fibra y densidad básica de la madera de especies del Sabana con fines productivos

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Abstract
The objective of this study was to qualify the wood of the species *Astronium fraxinifolium*, *Enterolobium gummiferum*, *Eriotheca pentaphylla*, and *Plathymenia reticulata* of the Brazilian Cerrado for forestry productive purposes based on the classification of their wood basic density and fiber quality indices. Discs were removed at a height of 1.3 m from the ground, and opposing wedges were obtained. The analyzed parameters were: wood basic density, fiber dimension, and fiber quality indices. The wood basic density was negatively correlated with fiber length and thickness. *E. pentaphylla* presented low basic density, long fiber length, and greater fiber wall thickness. On the other hand, *A. fraxinifolium*, *E. gummiferum*, and *P. reticulata* woods presented medium/high basic density, short fiber length, and quality indices that foster them for energy purposes, paper production, and use in floors and civil construction.
Keywords: Cell wall; Specific mass; Quality Index; Wall fraction.

Resumo
O objetivo deste trabalho foi qualificar a madeira das espécies *Astronium fraxinifolium*, *Enterolobium gummiferum*, *Eriotheca pentaphylla* e *Plathymenia reticulata* do Cerrado brasileiro para fins produtivos florestais, com base na densidade básica da madeira e nos índices qualitativos das fibras. Foram retirados discos na altura de 1,3 m do solo e obtidas cunhas opostas. Os parâmetros analisados foram: densidade básica da madeira, dimensão das fibras e índices qualitativos das fibras. Verificou-se que a densidade básica da madeira se correlacionou negativamente com o comprimento e espessura das fibras. *E. pentaphylla* apresentou baixa densidade básica, comprimento de fibras longo e maior espessura da parede das fibras. Já as madeiras de *A. fraxinifolium, E. gummiferum* e *P. reticulata* apresentaram

média/alta densidade básica, comprimento de fibras curto e índices qualitativos que as potencializam para fins energéticos, produção de papel e utilização em assoalhos e construção civil.
Palavras-chave: Parede celular; Massa específica; Índice de qualidade; Fração da parede.

Resumen
El objetivo de este estudio fue calificar la madera de las especies *Astronium fraxinifolium*, *Enterolobium gummiferum*, *Eriotheca pentaphylla* y *Plathymenia reticulata* del Cerrado brasileño con fines productivos forestales, con base en la clasificación densidad básica de la madera y los índices cualitativos de las fibras. Se retiraron discos a una altura de 1,3 m del suelo de los árboles y se obtuvieron cuñas opuestas. Los parámetros analizados fueron: densidad básica de la madera, dimensión de fibra e índices cualitativos de fibra. Se verificó que la densidad básica de la madera se correlacionó negativamente con la longitud y espesor de las fibras. En el cual, *E. pentaphylla* presentó baja densidad básica, longitud de fibra larga y mayor espesor de pared de fibra. Mientras que las maderas de *A. fraxinifolium*, *E. gummiferum* y *P. reticulata* presentaron densidad básica media/alta, longitud de fibra corta e índices cualitativos que las potencializan para fines energéticos, producción de papel y uso en pisos y construcción civil.
Palabras clave: Pared celular; Masa específica; Índice de calidad; Fracción de pared.

1. Introduction

The quality of a wood refers to its ability to meet the requirements to manufacture a particular product (Gonçalez et al., 2006). Among the main characteristics that express this quality is density, which is directly related to the volume of empty spaces in the wood. In addition to being a relatively easy-to-determine property, density is related to important environmental, technological, and economic aspects and to climate variables such as precipitation and temperature (Oliveira et al., 2021). It is also associated with other wood characteristics, such as contraction, swelling, and mechanical resistance of pieces (Schulgasser & Witztum, 2015; Amer et al., 2021; Gonya et al., 2021). Moreover, density influences the production and quality of charcoal (Zanuncio et al., 2013; Silva et al., 2020; Couto et al., 2022), as well as operational costs regarding transport and storage (Pereyra et al., 2006).

For the pulp and paper industry, for example, density is directly related to the higher productivity in the pulping process, considering the production of cellulose pulp by volume in the digester. Thus, it influences its yield and quality (Mokfienski, 2004). However, wood with a basic density of 400 to 550 kg m^{-3} is recommended as dense woods require more drastic cooking in terms of temperature and alkali load, which can increase process costs and reduce yield (Gomide et al., 2005; Vidaurre et al., 2020).

Another important characteristic for qualification is wood anatomy. Determining the fiber dimensions, measured by its length, width, wall thickness, and lumen diameter, allows to estimate quality indices and classify the wood, even if preliminarily. According to Foelkel (2010), the fiber dimensions exert a direct influence on the variables of the pulp production process, such as the degree of refining, quality of the pulp, and physical and mechanical strength of the paper. Thus, the determination of these indices, such as fiber wall fraction, enables the prediction of the cellulose pulp behavior for papermaking (Baldin et al., 2017). Charcoal is also related to the fiber cell wall, maintaining its mainly morphological characteristics (Baraúna et al., 2021). The anatomical parameters directly reflect the wood basic density, and fibers with thick cell walls have a greater volume of biomass (Santos et al., 2011). In this way, when morphologically analyzing wood fibers, auxiliary information can be obtained by indicating species with potential for the forestry sector.

Knowing the quality of wood of native species, especially from areas with sustainable management, can lead to environmental and financial gains in a property or community (Guma, 2013). Studies concerning the quality of wood of species from the Cerrado – the second largest biome in Brazil, which stands out for the presence of trees with biomass frequency and production – are essential to assist in the Sustainable Forest Management Plan. Using these managed species, in alliance with the Paris Agreement (UN, 2015), can minimize the consequences of global warming and encourage the reforestation and cultivation of native species. In this context, the objective of this study was to qualify the wood of the species

Astronium fraxinifolium, *Enterolobium gummiferum*, *Eriotheca pentaphylla*, and *Plathymenia reticulata* of the Brazilian Cerrado for productive purposes in the forestry sector, based on the wood basic density and fiber quality indices and dimensions.

2. Methodology

2.1 Material collection

Discs at DBH (diameter at the height of 1.3 m from the ground) of four forest species native to the Cerrado biome (*Astronium fraxinifolium*, *Enterolobium gummiferum*, *Eriotheca pentaphylla*, and *Plathymenia reticulata*) were used. Three trees of each species were collected, and all specimens came from areas of remaining vegetation characterized as the Seasonal Semideciduous Forest of the Cerrado, in the state of Minas Gerais, Brazil (Table 1).

Table 1. Collection place of the four forest species under study.

Species	Popular name	Family	Collection place	Coordinates
Astronium fraxinifolium	Gonçalo-alves	Anacardiaceae	Montes Claros	16º 41’ 04’’S 43º 50’ 50’’W
Enterolobium gummiferum	Timburi-do-cerrado	Fabaceae	Carbonita	17º 32’ 23’’S 43º 8’ 21’’W
Eriotheca pentaphylla	Imbiruçu-branco	Malvaceae	Conceição do Mato Dentro	18°53’ 87’’S 43°25’ 98’’W
Plathymenia reticulata	Vinhático	Fabaceae	Carbonita	17º 33’ 97”S 43º 7’ 23”W

Source: Authors (2022).

According to the Köppen-Geiger classification, the climate of the municipalities of Montes Claros, Carbonita, and Conceição do Mato Dentro (Minas Gerais, Brazil) is of the Aw type, with tropical characteristics. There is a rainy season in summer, from November to April, and a dry season in winter, from May to October. The average temperature of the coldest month is above 18 ºC, and the annual rainfall is above 750 mm, reaching 1800 mm (Golfari et al., 1978). Montes Claros has an average annual temperature of 23.1 °C and an average annual rainfall of 869 mm; Carbonita has an average annual temperature of 21.9 ºC, with an average annual rainfall of 855 mm; and Conceição do Mato Dentro has an average annual temperature of 21.3 ºC and an average annual rainfall of 1406 mm (Climate-data.org, 2022).

2.2 Wood characterization

Opposing wedges were made from the DBH discs. Two opposing wedges were used to determine the wood basic density (WDB) according to NBR 11941 (ABNT, 2003), i.e., using the ratio between the dry mass of wood and its saturated volume.

The two remaining opposing wedges were used for wood anatomy studies. Small fragments of sapwood were removed to make macerating blades. The woody tissue disintegration was performed based on the macerating solution of hydrogen peroxide, acetic acid, and distilled water, according to the methodology of Mady (2007). Three slides were made per species. Using an optical microscope with a coupled camera and an image acquisition system, 25 readings were taken for the length (L), total diameter (TD), lumen diameter (LD), and wall thickness (WT) of fibers.

Based on the mean values of the fiber dimensions of each species, it was possible to calculate the fiber quality indices of wall fraction (WF), flexibility coefficient (FC), Runkel index, Mulsteph index, and Boiler incidence, according to Mulsteph

(1940), Barrichelo and Brito (1976) and Foelkel et al. (1978) (Table 2).

Table 2. Expressions used in the research of fiber quality indices of the species under study.

Parameters	Expressions
Wall Fraction (%)	$\frac{2 * WT}{FD} * 100$
Flexibility Coefficient (%)	$\frac{LD}{FD} * 100$
Runkel Index	$\frac{2 * WT}{LD}$
Mulsteph Index	$\frac{FD^2 - LD^2}{FD^2}$
Boiler Incidence	$\frac{FD^2 - LD^2}{FD^2 + LD^2}$

Where: WT = Wall thickness; FD = Fiber diameter; LD = Lumen diameter. Source: Authors (2022).

2.3 Statistical analysis

Data were submitted to Shapiro-Wilk tests to assess the normality of residuals. Subsequently, they were evaluated by means of the analysis of variance (ANOVA) and Tukey test at 5% significance. To determine the correlations between wood basic density and fiber dimensions, Pearson's correlation coefficient was obtained at a 5% significance level. All statistical analyzes were performed with the aid of the R Core Team (2019) software.

3. Results and Discussion

3.1 Basic density and fiber dimensions

There was a statistical difference between the studied species for wood basic density (WBD) (Table 3). *Plathymenia reticulata* wood presented values 2.3 times higher than *Eriotheca pentaphylla* – the species with the lowest density – and 1.4 and 1.2 times higher than *Enterolobium gummiferum* and *Astronium fraxinifolium* woods, respectively. However, it is worth noting that these specimens were collected at different ages and environments, with a medium-to-advanced stage of regeneration, which influences the results given that age, growth rate, genotype, place of origin, soil, and climate factors have a direct effect on wood density (Valério et al., 2008).

Table 3. Mean values, confidence interval, and Pearson's correlation of the basic density and fiber dimension of species under study.

Species	WBD (Kg m^{-3})	Fiber (µm)			
		L	FD	LD	WT
A. fraxinifolium	632 b (±36.11)	865.90 c (±49.64)	22.58 ab (±1.56)	13.99 a (±1.32)	4.30 bc (±0.42)
E. gummiferum	548 c (±30.81)	853.06 c (±54.77)	23.13 ab (±1.41)	13.76 ab (±1.41)	4.69 b (±0.43)
E. pentaphylla	327 d (±3.66)	1904.04 a (±65.63)	25.43 a (±0.84)	11.62 b (±0.63)	6.91 a (±0.33)
P. reticulata	777 a (±9.86)	997.96 b (±70.72)	17.30 b (±1.06)	9.40 c (±0.93)	3.95 c (±0.20)
Pearson's Correlation of Basic Density		-0.6358**	-0.3217	0.0098	-0.5565**

Where: WBD = Wood basic density; L = Length; FD = Fiber diameter; LD = Lumen diameter; WT = Wall thickness. ( ) = Confidence interval. Means followed by the same letter in the same column do not differ statistically from each other by the Tukey test at 5% significance. **Significant at 5% significance. Source: Authors (2022).

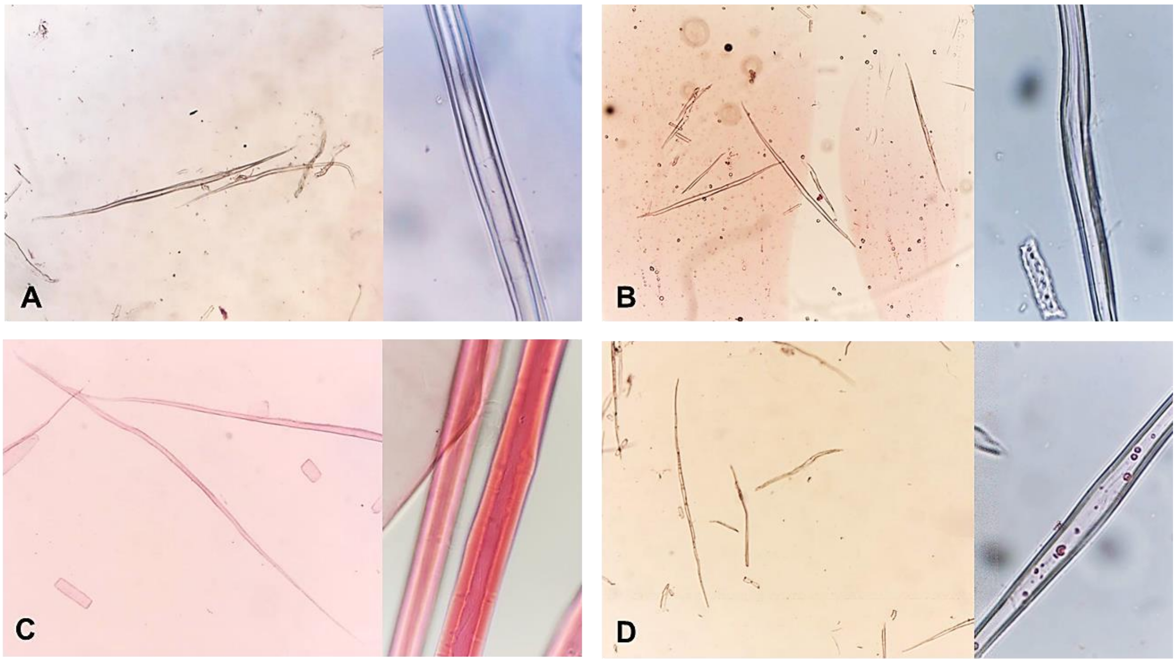
The classification in terms of WBD allows directing the studied species according to products and quality. *E. pentaphylla* wood was classified as having low density, *A. fraxinifolium* and *E. gummiferum* woods as medium density, and *P. reticulata* wood as high density (Melo et al., 1992). Thus, the last three species are indicated for floors and civil construction, for example, given that species with medium and high density are commonly used in these industries (Lobão et al., 2011).

For charcoal production, *A. fraxinifolium*, *E. gummiferum*, and *P. reticulata* are within the average required by the sector (> 500 kg m^{-3}) (Protásio et al., 2021). *P. reticulata* wood stands out since the higher the wood density, the higher the density and mechanical strength of the charcoal produced (Pereira et al., 2012; Couto et al., 2022). As for the pulp and paper industry, only *E. gummiferum* wood is within the required average (400 to 550 kg m^{-3}). Woods with high density present higher alkali consumption since they have thicker fibers, increasing the process costs (Silva, 2011).

The results for basic density were consistent with those described in the literature for Savannah species, which range from 200 to 845 kg m^{-3} (Vale et al., 2002; Silva et al., 2015; Siqueira et al., 2020), and similar to those presented for *E. gummiferum* (620 kg m^{-3}), *Eriotheca gracilipes* (360 kg m^{-3}), *P. reticulata* (750 kg m^{-3}) and *A. fraxinifolium* (610 kg m^{-3}) (Vale et al., 2002; Testoni et al., 2009; Oliveira, 2014). Besides, WDB values close to 659 kg m^{-3} were reported for different species from the Cerrado of Minas Gerais (Oliveira et al., 2021), the same region as the trees collected in this study.

Regarding the anatomical analysis, only *A. fraxinifolium* and *E. gummiferum* showed no statistical differences, being considered similar in terms of fiber dimensions (Table 3). This can be explained by the fact that they have the same classification for wood basic density and that the anatomical characteristics of wood directly reflect on its density. These species had values for fiber length 2.2 times lower than *E. pentaphylla*, the longest species. Thus, *A. fraxinifolium*, *E. gummiferum*, and *P. Reticulata* were classified as having short fibers, which is characterized by a big number of fibers for a certain amount of wood. The same behavior was found for *Eucalyptus* wood ranging from 700 to 1,300 µm (Silva, 2005). *E. pentaphylla* was classified as having long fibers (Figure 1).

Figure 1. Anatomical fibers of wood species native to the Cerrado in the state of Minas Gerais, Brazil: *Astronium fraxinifolium* (A), *Enterolobium gummiferum* (B), *Eriotheca pentaphylla* (C), and *Plathymenia reticulata* (D).



Where: 5x objective for length measurement (µm). 40x objective for width measurement (µm). Source: Authors, (2022).

For fiber diameter and fiber wall thickness, *E. pentaphylla* wood stood out with the highest values and statistical differences compared to the others. However, all studied species were classified as having medium-width fibers, narrow lumen diameter, and thin-to-thick walls (IAWA, 1989). The mean value for fiber length and fiber wall thickness of *E. pentaphylla* presented by Barros (2006) was 2,005 µm and 7.55 µm, respectively, similar to those of the present study. Thus, the results obtained in this research for fiber dimensions of forest species were consistent with those presented in the literature for Savannah species, with a variation from 688 to 2,052.9 µm for length; 12 to 27.7 µm for diameter; 1.6 to 16.3 µm for lumen diameter; and 4.3 to 11.5 µm for fiber wall thickness (Paula, 2005; Paes et al., 2013; Faria et al., 2020).

Vital (1984) mentions that wood density tends to increase considering the tree age and as a function of the increase in wall thickness. However, in the present study, the fiber wall length and thickness were negatively correlated with the basic density. *E. pentaphylla*, for example, presented low density, and its anatomical dimensions were superior to the other species (Table 3).

Given that the anatomical structure of wood depends on growth conditions and that the variability of its dimensions can be seen not only at the level of genus and species (Gonçalez et al., 2014), the results for Pearson's correlation can be explained by the specificity of each individual. In addition, even with thicker fiber walls, *E. pentaphylla* may have in its anatomical composition a higher percentage of light tissues with empty spaces, such as parenchyma and vascular elements, thus contributing to the values found in this research. For better use of the material, the complete anatomical characterization of the forest species are recommended, in which they should be performed on trees of several ages and even in different crop conditions.

Fiber quality indices

Wood quality indices, determined based on fiber dimensions, provided a previous diagnosis of the quality of the species, especially for the pulp and paper industry. Regarding the fiber morphology, *A. fraxinifolium* and *E. gummiferum* did not differ statistically. *E. gummiferum* and *P. reticulata* were also similar, showing a significant difference only for the Mulsteph index. *E. pentaphylla* presented a significant difference in all parameters (Table 4).

Table 4. Mean values and confidence interval of fiber quality indices of the species under study.

Species	WF (%)	FC (%)	Runkel	Mulsteph	Boiler
A. fraxinifolium	38.51 C (±2.55)	61.49 A (±2.55)	0.64 C (±0.07)	0.62 C (±0.03)	0.45 C (±0.03)
E. gummiferum	41.23 BC (±3.46)	58.77 AB (±3.46)	0.74 BC (±0.11)	0.65 C (±0.04)	0.49 BC (±0.04)
E. pentaphylla	54.32 A (±1.84)	45.68 C (±1.84)	1.22 A (±0.10)	0.79 A (±0.02)	0.65 A (±0.02)
P. reticulata	46.33 B (±2.61)	53.67 B (±2.61)	0.90 B (±0.10)	0.71 B (±0.03)	0.55 B (±0.03)

Where: WF = Wall fraction; FC = Flexibility coefficient. ( ) = Confidence interval. Means followed by the same letter in the same column do not differ statistically from each other by the Tukey test at 5% significance. Source: Authors (2022).

For the flexibility coefficient (ease of union between fibers), only *E. pentaphylla* did not present favorable results for the pulp and paper industry, with values 1.4 times higher than *A. fraxinifolium*, the most suitable species for this purpose. Values between 0.50 and 0.75 classify fibers as flexible, which tend to form a highly resistant paper when interlaced (Bektas et al., 1999). Thus, the lower this index, the higher the possibility of tearing collapse and opacity (Foelkel et al., 1978).

With regards to cell wall fraction (ease of collapse and flexibility for fiber binding), the studied species are within the limit of up to 60%, recommended by Foelkel et al. (1978). However, when the wall fraction has a percentage superior to 40%, the fibers tend to be more rigid and difficult to collapse, consequently producing a looser net paper (Foelkel, 2007). Thus, *E. pentaphylla* is not indicated for pulp and paper production because, in addition to presenting a basic density lower than 400 kg m^{-3}, its values for flexibility coefficient and wall fraction are not favorable, being 1.3 times lower than the recommended.

The charcoal industry considers the index of fiber wall fraction as it is related to the higher presence of components that can generate energy. In this sense, only *A. fraxinifolium* presented satisfactory values for energy purposes (> 60%) (Paula, 2005). However, *P. reticulata* is also a viable option for this sector due to its high basic density.

Considering the Runkel index (firmness and stiffness of fibers), *A. fraxinifolium*, *E. gummiferum*, and *P. Reticulata* were considered good for paper production, while *E. pentaphylla* fibers were regular, according to the classification of Barrichelo e Brito (1976). Values close to or higher than 1, such as those in the present study, are more suitable for the production of absorbent papers since, as this value increases, the lumen diameter decreases and the fiber walls become thick, thus boosting the absorption capacity of paper (Rodrigues, 2010).

For the Mulsteph and Boiler indices (fiber collapse capacity), only *A. fraxinifolium* and *E. gummiferum* did not present recommended values for paper production (< 0.50). These values are related to the smaller relative area of the cell wall, indicating thin walls (Pego et al., 2019). The results for the quality indices are in accordance with those obtained by Faria (2016) for species from the Savannah and by Boschetti et al. (2015) and Baldin et al. (2017) for *Eucalyptus* species, which is the most used genus in the forestry sector.

Thus, determining the fiber dimensions is important to evaluate the quality of wood for the production of different types of papers. For better use of the material, the complete technological characterizations of the forest species are recommended. Knowing these wood species, in line with sustainable management, can reduce the pressure on other species prohibited from cutting, which may be a possibility of association with traditionally used species.

4. Conclusion

Astronium fraxinifolium and *Enterolobium gummiferum* woods were classified as having medium basic density and had similar fiber dimensions. *Plathymenia reticulata* was classified as having high basic density and short fibers, and *Eriotheca pentaphylla* was classified as having low density, long fiber length, and greater fiber wall thickness.

According to their basic density and fiber quality indices, *A. fraxinifolium*, *E. gummiferum*, and *P. reticulata* woods have potential and quality for energy purposes, paper production, and use in floors and civil construction. Besides, wood technology associated with management and silviculture and further investigations on the species and their co-products are indicated.

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