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Scientific Article

WOOD PROPERTIES OF THREE SOUTH AMERICAN SPECIES PLANTED IN CONSORTIUM

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ABSTRACT

The use of tropical wood species in reforestation can be an alternative resource to meet the demand from the industrial wood sector. However, this strategy remains very limited, even while tropical forests continue to be deliberately exploited for the selective extraction of native species of highly commercial value. To test the potential of tropical species in reforestation, it is first necessary to evaluate the production and quality of the wood produced. Therefore, this study aimed to evaluate the quality *Astronium urundeuva*, *Astronium fraxinifolium* and *Terminalia argentea* woods, all aged 22 years, from a heterogeneous plantation located in the municipality of Selvíria-MS. From each species, 15 trees were selected. A 10 cm thick disc was removed from the base of each tree. Samples were taken from the discs near the bark region to evaluate the anatomical characteristics and the physical and mechanical properties of the wood. According to the results, it was found that only compressive strength did not differ significantly among the species. *Astronium urundeuva* presented the highest values for basic density and apparent density, and *Terminalia argentea* presented the highest values for fiber length, fiber wall thickness and vessel element diameter. The best Pearson correlations were found for basic density and apparent density, both for *Astronium fraxinifolium* and *Astronium urundeuva*. The best regression equations obtained were correlations between basic density and apparent density for *Astronium fraxinifolium* and *Astronium urundeuva*. The linear model best fits the data for these correlations. The greater growth of *Terminalia argentea* trees caused lower wood density owing to the lower rate of competition among trees. Based on the results and according to wood strength standards, the three species can be classified in the D40 strength class. According to the obtained results, these can support information to be compared with some species used commercially for structural purposes and other uses.

Keywords: Forest management; Physicomechanical properties; Tropical Brazilian wood

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PROPRIEDADES DA MADEIRA DE TRÊS ESPÉCIES SUL-AMERICANAS PLANTADAS EM CONSÓRCIO

RESUMO – O uso de espécies madeireiras tropicais em reflorestamento pode ser uma alternativa para suprir demanda do setor industrial madeireiro, porém o uso ainda é muito limitado, e as florestas tropicais remanescentes ainda seguem sendo deliberadamente exploradas para extração seletiva de espécies nativas de alto valor comercial. Para testar o potencial das espécies tropicais em reflorestamento é necessário avaliar produção e a qualidade da madeira produzida. Sendo assim, este estudo visa avaliar a qualidade da madeira de *Astronium urundeuva*, *Astronium fraxinifolium* e *Terminalia argentea* aos 22 anos oriundas de um plantio heterogêneo, localizado no município de Selvíria-MS. De cada uma das espécies foram selecionadas 15 árvores. De cada árvore foi retirada um disco de 10 cm de espessura da base. Dos discos foram tomadas amostras nas proximidades da região casca para a avaliação das propriedades da madeira. Para isso foram avaliadas as características anatômicas e propriedades físicas e mecânicas das madeiras. De acordo com os resultados verificou-se que somente a resistência à compressão paralela não se diferenciam significativamente entre as espécies. *Astronium urundeuva* apresentou os maiores valores para densidade básica e densidade aparente e a *Terminalia argentea* para comprimento se fibra, espessura da parede da fibra e diâmetro de elemento de vaso. As melhores correlações de Pearson foram encontradas para a densidade básica e densidade aparente, tanto para o *Astronium fraxinifolium* quanto para *Astronium urundeuva*. As melhores equações de regressões obtidas foram para a relações entre densidade básica e densidade aparente para o *Astronium fraxinifolium* e *Astronium urundeuva*, sendo que o modelo linear foi o que melhor ajustou os dados dessas relações. O maior crescimento das árvores de *Terminalia argentea* ocasionou uma menor densidade da madeira devido a menor taxa de competição entre as árvores. Com base nos resultados e segundo as normas de resistência da madeira, as três espécies podem ser classificadas na classe de resistência D40. Os resultados obtidos podem subsidiar informações que permitam a comparação com espécies utilizadas comercialmente para fins estruturais e outros usos.

Palavras-Chave: Manejo florestal; Propriedades físico-mecânicas, Madeira tropical brasileira

1. INTRODUCTION

In 2022, the total area of cultivated trees in Brazil was 9.94 million hectares. We highlight that this sector's growth commonly occurs on previously degraded lands and includes species of *Pinus* and *Eucalyptus* that occupy most planted areas. However, around 360 thousand hectares have been planted with other exotic and native species, including *Hevea brasiliensis*, *Acacia* spp. and *Tectona grandis* (Indústria Brasileira de Árvores - IBÁ, 2023).

Forest plantations with native species play an important role in promoting sustainable landscapes in the tropics. However, the use of native species with potential for industrial use is still very limited, and remaining tropical forests continue to be deliberately exploited for the selective extraction of native species of highly commercial value (Piotto et al., 2018). The planting of tree species in consortium, or, according to Andrade Neto et al. (2015), with other crops, is a good alternative production system for rural properties and family farming.

Reforestation with native species should promote increased resilience and maintain, or improve, the capacity to adapt to climate change, especially in the long term, along with conserving biodiversity, including the most threatened populations, and keeping forest stands in good condition, these species have the ability to produce wood to supply the market without putting pressure on the remaining forests (Carvalho, 2021).

However, to establish best practices of reforestation, it is essential to understand the potential of a given species to produce quality wood for various industrial purposes. Therefore, studies with progeny testing, base population testing, and seed orchards are used for ex situ conservation and can provide results that guide the development of planting strategies, as well as provide materials for studying wood quality (Siqueira et al., 2000). Such results can contribute to 1) genetic conservation through progeny tests, indicative of the potential for conservation of germplasm banks (ex situ); 2) planning and production of seeds for the restoration of degraded areas; and 3) a knowledge base that includes an assessment of wood quality between provenances (Lima et al., 2015).

Among the various native, non-endemic species with potential for use in reforestation on the South American continent, we highlight the species *Astronium fraxinifolium*, *Astronium urundeuva* and *Terminalia argentea*. These species are thought to have commercial value for different industrial uses based on wood properties.

Astronium fraxinifolium occurs in Argentina (Martinez-Crovetto, 1963), Bolivia (Killeen et al., 1993), Honduras (Thirakul, 1998), Paraguay (Lopez et al., 1987) and Venezuela (Barkley, 1968). In Brazil, *A. fraxinifolium* is characteristic of the Brazilian Savanna areas of Central Brazil (Minas Gerais, Goiás and Mato Grosso) and the Amazon (Pará). It is a deciduous, heliophytic plant typical of rocky and dry terrains where it forms discontinuous groups, varying from 6-8 m in height and 60-80 cm in diameter (Lorenzi, 1998).

Astronium urundeuva occurs on the North American continent from Mexico to Argentina (Maia, 2004), and it is endemic to extreme northwestern Argentina (Castiglioni, 1975), southern and eastern Bolivia (Killeen et al., 1993), and Paraguay (Lopez et al., 1987). In Brazil, it has a natural distribution that covers areas from Ceará ("caatinga" biome) to the states of São Paulo and Mato Grosso do Sul, occurring preferentially in dry and rocky terrains in dense groups, both in open and very dry formations ("caatinga") as in tropical rainforest (Lorenzi, 1998). Carvalho (2003) recommended mixed planting of this species in association with a fast-growing pioneer species to obtain individuals with a straighter stem. *A. urundeuva*, in consortium with an initial secondary species, presents good development, and its silvicultural characteristics can vary, reaching a height of up to 15 m with a trunk diameter of up to 100 cm (Kageyama et al., 1987).

Terminalia argentea occurs in Bolivia (Killeen et al., 1993) and Paraguay (Lopez et al., 1987). In Brazil, it occurs in the states of Minas Gerais, Mato Grosso do Sul and São Paulo. It is a deciduous, heliophytic, pioneer plant adapted to dry and poor terrain, which is characteristic of the Brazilian Savanna and its transition to semi-deciduous seasonal forest. It generally occurs in more or less dense groups and preferably on hilltops and high slopes where the soil is well drained, both in primary forest and secondary formations. It is excellent for mixed plantings in degraded areas. When planted in the field, the plants show moderate development, reaching a height of 8 to 16 m and a trunk diameter of 40 to 50 cm (Lorenzi, 1998).

A proper analysis of wood properties that affect quality is an essential prerequisite for choosing the best use for a given species. Especially, trees are subjected to constant variations in, for example, humidity, soil conditions and spacing that, in turn, cause variations in wood properties, even wood free from defects, such as knots or high grain alteration (Kretschmann, 2010).

In this study, the wood properties of three South American species planted in a consortium (*A. fraxinifolium*, *A. urundeuva*, and *T. argentea*) were investigated. We hypothesize the presence of differences in wood properties among these three species. To test this hypothesis, we aimed 1) to determine some physicomechanical and anatomical properties of woods and 2) correlate variables to better understand the influence of anatomy on physicomechanical properties. The key contribution of this investigation arises from characterizing and comparing wood properties among these three species planted in a consortium. We anticipate that our results can serve as a reference for foresters engaged in strategic planning for the conservation of these species in reforestation projects with the aim of providing stocks for industrial use of the woods under study.

2. MATERIAL AND METHODS

2.1 Experimental area

The progeny test was installed at FEPE/FEIS/UNESP, which is located in the municipality of Selvíria-MS at an altitude of 375 m, latitude of 20º19'S and longitude of 51º26'W (Figure 1). The local climate is Aw, according to the Köppen classification, with an average annual temperature of 23 °C and average annual precipitation of 1,440 mm (Alvares et al., 2013) . The local soil is classified as dystrophic Red Oxisol (LVd) typical clayey (Santos et al., 2018).

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Figure 1. Geographic location of the forest fragment and the progeny test in the Fazenda de Ensino, Pesquisa e Extensão (FEPE), in Selvíria-MS. (Maps from Pinterest, Wikipedia and location via Google Earth)

Figura 1. Localização geográfica do fragmento florestal e do teste de progênies na Fazenda de Ensino, Pesquisa e Extensão (FEPE), em Selvíria-MS. (Mapas de Pinterest, Wikipedia and localização pelo Google Earth)

2.2 Planting

To form the experimental planting, seeds were collected from 28 free-pollinated trees in each of the species studied (*Astronium fraxinifolium*, *Astronium urundeuva* and *Terminalia argentea*) located in Selvíria-MS. The experimental design used was randomized blocks, considering 28 treatments (progenies) and four replications for each of the species studied. The plots installed in the experiment followed a linear arrangement, alternating the species every 10 plants per plot with spacing of 3.0 m x 1.5 m. Thus, a test of progenies of *Astronium urundeuva*, *Astronium fraxinifolium* and *Terminalia argentea* was formed in a consortium in an area of 1,446 hectares (Figure 2a).

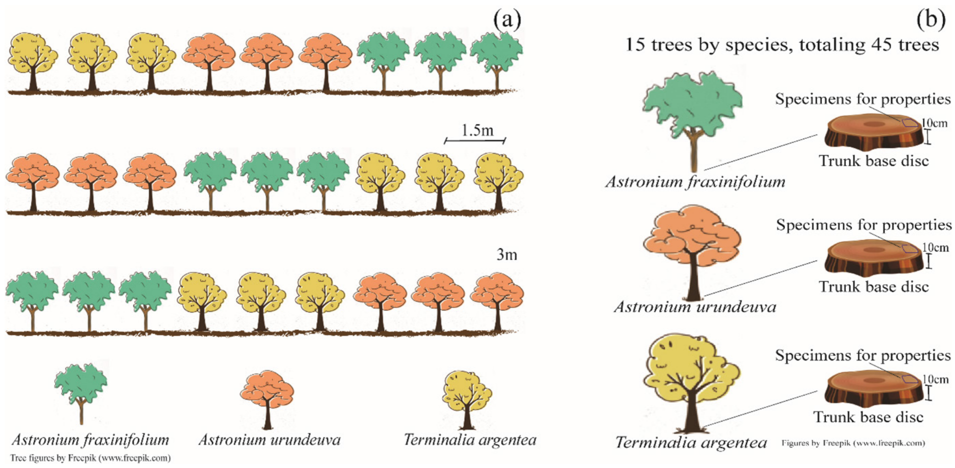

Figure 2. Sketch demonstrating the experimental design and spacing of trees for planting in a consortium of three species (*Astronium fraxinifolium*, *Astronium urundeuva* and *Terminalia argentea*) [a] and Schematic illustration of sampling for wood properties [b]

Figura 2. Croqui demonstrando o desenho experimental e espaçamento de árvores para o plantio em consórcio de três espécies (*Astronium fraxinifolium*, *Astronium urundeuva* e *Terminalia argentea*) [a] e Ilustração esquemática da amostragem para propriedades da madeira [b]

2.3 Sampling

Sampled trees were measured for total height, commercial height, and diameter at breast height (1.30 m above the ground). Planting survival rate was measured for each species at 22 years (Table 1) at which time 15 trees of each species were selected disregarding the progenies, to study wood properties. A 10 cm thick disc was collected from each tree at its base. Representative samples were taken from each disc close to the bark region from which specific specimens were removed to assess wood quality (Figure 2b).

Table 1. Total height (TH), commercial height (CH), diameter at breast height (DBH) (1.30 m above the ground), survival rate (SR) and mean annual increment in solid wood volume (MAI_{swv}) of 22-year-old *Astronium fraxinifolium*, *Astronium urundeuva* and *Terminalia argentea*

Tabela 1. Altura total (TH), altura comercial (CH) e diâmetro à altura do peito (DBH) (1,30 m acima do solo), taxa de sobrevivência (SR) e incremento médio anual em volume de madeira sólido (MAI_{swv}) de *Astronium fraxinifolium*, *Astronium urundeuva* e *Terminalia argentea* aos 22 anos

Species	TH (m)	CH (m)	DBH (cm)	SR (%)	MAI_{swv} (m^3 ha^{-1} $year^{-1}$)
Astronium fraxinifolium	10.64	6.31	11.32	86	2.73
Astronium urundeuva	11.20	5.31	10.71	88	2.48
Terminalia argentea	12.41	6.45	15.87	60	3.98

2.4 Wood properties

To evaluate wood quality, physicomechanical and anatomical properties were analyzed. The mechanical tests were carried out with dry samples in an environment with a normalized temperature until they reached 12% humidity, the standard reference condition, in accordance with the recommendation of NBR7190-1 (ABNT, 2022). To obtain compressive strength parallel to the fibers (f_{c0}), specimens measuring 2 x 2 x 6 cm were used, and a total of 45 specimens were obtained from one disc each. Compression tests were carried out on a universal testing machine, according to the adapted NBR 7190-3 standard (ABNT, 2022).

To obtain the apparent density (ρap), samples measuring 2 x 2 x 6 cm were taken from the same discs as noted above and dried until reaching 12% moisture. Dimensions of the samples were measured with a digital caliper with a sensitivity of 0.01 cm, and the mass of each specimen was obtained on a semi-analytical digital scale with a sensitivity of 0.01 g, following the adapted NBR 7190-3 standards (ABNT, 2022). To determine basic density (ρbas), samples measuring 2 x 2 x 6 cm were used, and the hydrostatic balance method was used in accordance with NBR 11941 (ABNT, 2003).

To study the anatomical dimensions of the wood, small portions from each sample were macerated using Franklin's method (Berlyn and Miksche, 1976, modified), stained with aqueous safranin and mounted temporarily in water and glycerin (1:1). Samples (2cm^3) were softened in boiling water and glycerin (4:1) for 1 h. Transverse sections 15-20 µm thick were cut using a sliding microtome. Sections were bleached with sodium hypochlorite (60%), washed thoroughly in water, and stained with 1% safranin (Johansen, 1940). Anatomical measurements followed the recommendations of the IAWA Committee (1989). Quantitative data are based on at least 25 measurements for each feature, thus fulfilling the statistical requirements for the minimum number of measurements according to the IAWA Committee (1989). Anatomical measurements were obtained using an Olympus CX 31 microscope equipped with a camera (Olympus

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E330 EVOLT) and computer image analysis software (Image-Pro 6.3).

2.5 Statistical procedures

In the statistical analysis of the data, the homogeneity of variances was tested using the Bartlett test at 5% significance and the distribution of residues using the Shapiro-Wilk test at 5% significance. Subsequently, the F test for analysis of variance was carried out using a completely randomized experimental design to study the properties. The Tukey test was used to compare means when the F test was significant at 5%. Descriptive analyses, Pearson's correlation test, and regression analysis were also performed. The correlation values used in the present study are categorized as follows: very weak (0.01 – 0.20), weak (0.21 – 0.40), moderate (0.41 – 0.60), strong (0.61 – 0.80), and very strong (0.81 – 0.99) (Lopes, 2016). Statistical analyses were performed using R software (R Core Team, 2019).

3. RESULTS

According to the Shapiro-Wilk test, the residuals were considered normal for all variables under study. Also using the Bartlett test, variances were considered homogeneous. ANOVA results demonstrated that only compressive strength did not differ significantly among the species (Table 2).

Table 2. Summary of analysis of variance for basic density (ρbas), apparent density (ρap), compression parallel (f_{c0}), fiber length (FL), fiber wall thickness (FWT), vessel diameter (VD), and vessel frequency (VF) of 22-year-old *Astronium fraxinifolium*, *Astronium urundeuva*, and *Terminalia argentea* woods

Tabela 2. Resumo da análise de variância para densidade básica (ρbas), densidade aparente (ρap), compressão paralela (f_{c0}), comprimento da fibra (FL), espessura da parede da fibra (FWT), diâmetro do vaso (VD), frequência do vaso (VF) das madeiras *Astronium fraxinifolium*, *Astronium urundeuva* e *Terminalia argentea* aos 22 anos

Causes of variation	DF	Mean squares						
		ρ_{bas} (kg m^{-3})	ρ_{ap} (kg m^{-3})	f_{c0} (MPa)	FL (µm)	FWT (µm)	VD (µm)	VF (nº.mm^{-2})
Species	2	57431**	71656**	94.24n.s.	166704**	1.94**	3095**	9.06**
Residual	42	5128	6967	58.31	21011	0.26	219	0.08
mean		492	782	58	968	4.37	103	7.06
CV_e (%)		14.54	10.68	16.95	14.75	11.75	14.34	4.05

** 5% level of significance; n.s. = not significant and CV_e= coefficient of experimental variation. DF= degrees of freedom.

**Significativo ao nível de significância de 5%; n.s. = não significativo e CV_e= coeficiente de variação experimental. DF= graus de liberdade.

Both basic density and apparent density were higher in *A. urundeuva* and did not differ between *A. fraxinifolium* and *T. argentea* (Figures 3 a-b). For compressive strength, no significant difference was observed among the species (Figure 3 c). The lengths of fibers did differ statistically among the species. *T. argentea* showed the longest length 1074 µm, followed by *A. fraxinifolium* 968 µm, while the shortest length was exhibited by *A. urundeuva* 862 µm (Figure 3d). Thickness of fiber walls showed statistical differences among the species, and *T. argentea* showed the most thickness 4.74 µm (Figure 3e). For vessel diameter, *T. argentea* presented the highest value 120 µm, differing from the values of the other two species (Figure 3f). Vessel frequencies differed among species; *A. urundeuva* 7.84 nº.mm^{-2} presented the highest value, and *A. fraxinifolium* presented the lowest 6.28 nº.mm^{-2} (Figure 3g).

In the Pearson correlation study among the properties analyzed separately by species, we found very strong positive correlations

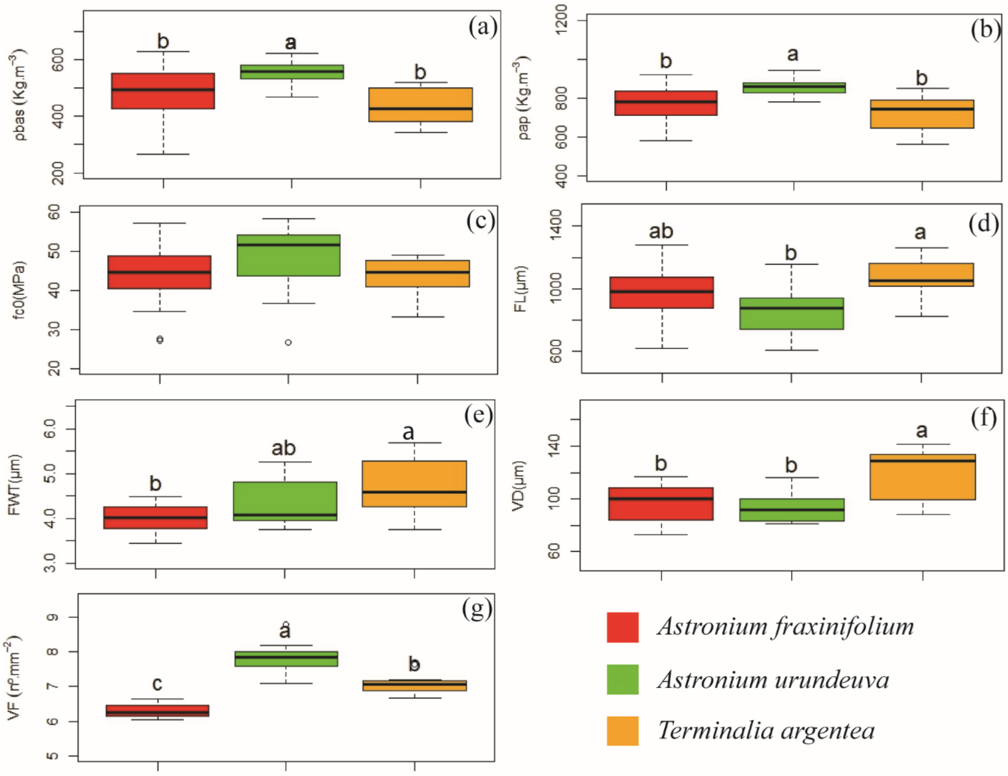
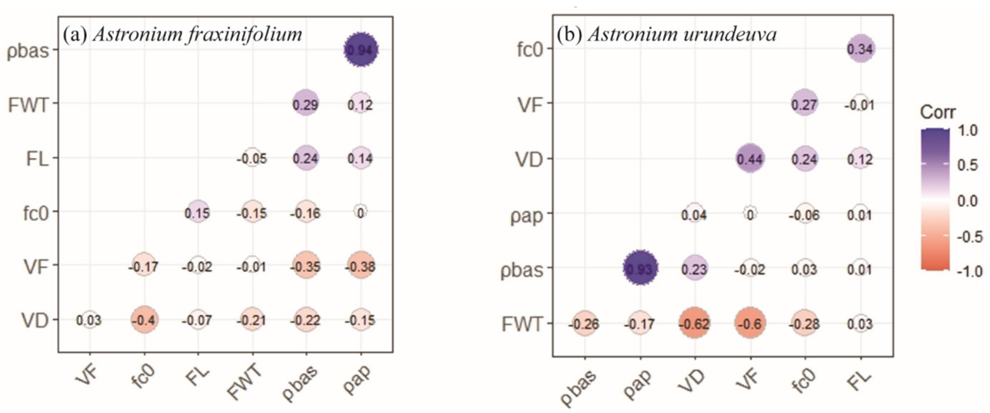


Figure 3. Basic density (ρbas) (a), apparent density (ρap) (b), compression parallel (fc0) (c) fiber length (FL) (d), fiber wall thickness (FWT) (e), vessel diameter (VD) (f) and vessel frequency (VF) (g) of 22-year-old *Astronium fraxinifolium*, *Astronium urundeuva* and *Terminalia argentea*

Figura 3. Densidade básica (ρbas) (a), densidade aparente (ρap) (b), compressão paralela (fc0) (c) comprimento da fibra (FL) (d), espessura da parede da fibra (FWT) (e), diâmetro do vaso (VD) (f) e frequência do vaso (VF) (g) de *Astronium fraxinifolium*, *Astronium urundeuva* e *Terminalia argentea* aos 22 anos

between basic density and apparent density, both for *A. fraxinifolium* (0.94) and *A. urundeuva* (0.93). In *T. argentea*, the best correlation was between apparent density and resistance to compression parallel to the fibers 0.64 (Figure 4a-c). In the cluster analyses, the separation of *A. urundeuva* as one isolated group and *A. fraxinifolium* and *T. argentea* as another isolated group was clear (Figure 4d).

In the regression analyses among properties, separated by species, it was found that the relationships between basic density and apparent density were strong for both *A.*



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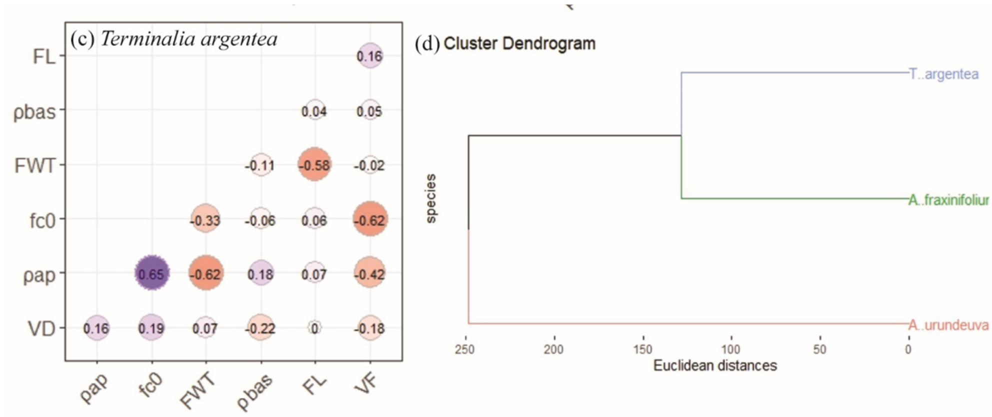


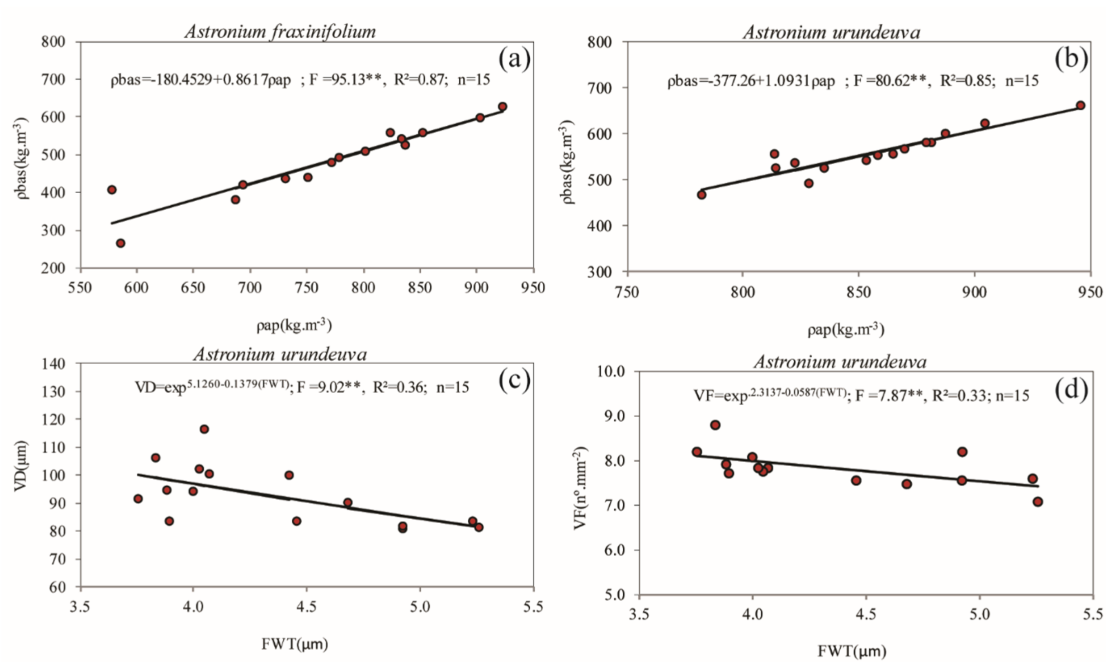
Figure 4. Pearson's Correlation Coefficient for basic density (ρbas), apparent density (ρap), compression parallel (fc0), fiber length (FL), fiber wall thickness (FWT), vessel diameter (VD) and vessel frequency (VF) by species separately of 22-year-old *Astronium fraxinifolium* (a), *Astronium urundeuva* (b), and *Terminalia argentea* (c). Negative and positive correlations are represented by red and blue, respectively. The magnitude of all correlations is represented by color intensity. The cluster dendrogram considered all analyzed variables (d)

Figura 4. Coeficiente de Correlação de Pearson para densidade básica (ρbas), densidade aparente (ρap), compressão paralela (fc0), comprimento da fibra (FL), espessura da parede da fibra (FWT), diâmetro do vaso (VD) e frequência do vaso (VF) por espécies separadamente, *Astronium fraxinifolium* (a), *Astronium urundeuva* (b) e *Terminalia argentea* (c) aos 22 anos. Correlações negativas e positivas são representadas por vermelho e azul, respectivamente. A magnitude de todas as correlações é representada pela intensidade da cor. Dendrograma de cluster, considerando todas as variáveis analisadas (d)

fraxinifolium (0.87) and *A. urundeuva* (0.85) (Figure 5a-b). Alternatively, other models exhibited varying relationships between the variables, albeit with a representativeness rate of approximately 29 to 39% (Figures 5c-h).

4. DISCUSSION

In general, *Astronium fraxinifolium* and *Astronium urundeuva* had the best survival rates at 22 years (86 and 88%, respectively),



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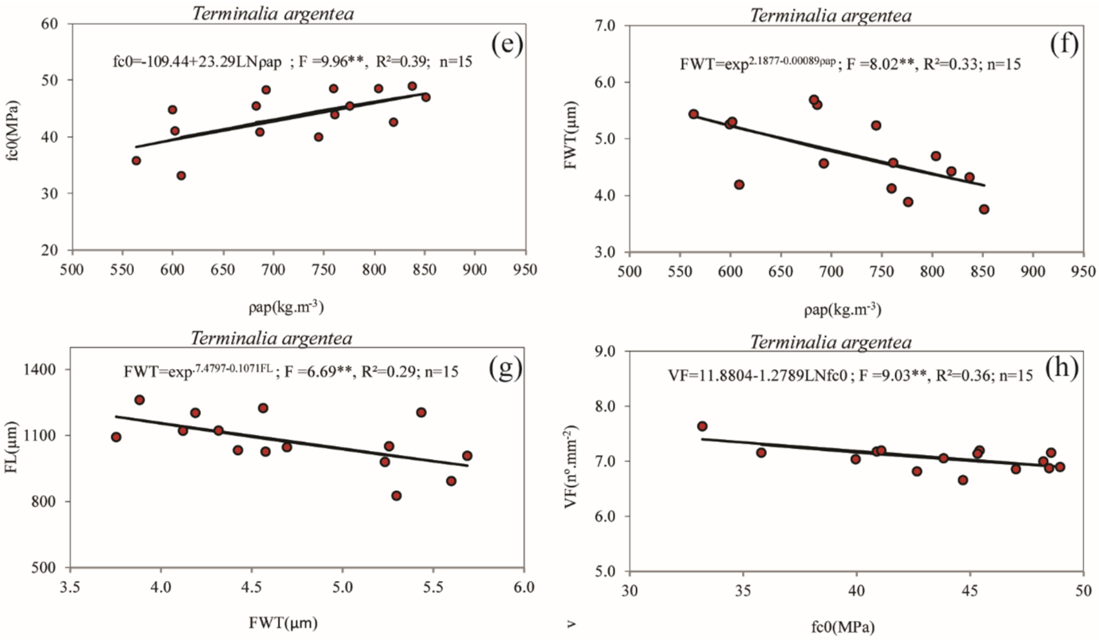

Figure 5. Relationships among basic density (ρbas), apparent density (ρap), compression parallel (fc0), fiber length (FL), fiber wall thickness (FWT), vessel diameter (VD) and vessel frequency (VF) of 22-year-old *Astronium fraxinifolium*, *Astronium urundeuva*, and *Terminalia argentea*

Figura 5. Relações entre densidade básica (ρbas), densidade aparente (ρap), compressão paralela (fc0), comprimento da fibra (FL), espessura da parede da fibra (FWT), diâmetro do vaso (VD) e frequência do vaso (VF) de *Astronium fraxinifolium*, *Astronium urundeuva* e *Terminalia argentea* aos 22 anos

reinforcing the idea that these species have good adaptability with the potential for use in consortium reforestation, acting as a late secondary. However, *Terminalia argentea* had a survival rate of 60%, indicating that it has good adaptability, but properties inferior to those of the other species (Table 1). However, this higher mortality over the years could possibly be explained the fact that *Terminalia argentea* is a pioneer species fulfilling its natural life cycle and, hence, leaving space for the arrival of new individuals, in addition, there was the development of the other two secondary species in a consortium (Cambuim, 2017).

This study investigated wood properties of three south American tree species planted in a consortium (*A. fraxinifolium*, *A. urundeuva* and *T. argentea*). In general, except for compression parallel to the grain, our results showed that all wood properties varied among species, supporting our initial hypothesis. *Astronium urundeuva* presented the highest values for basic density and apparent density, and *Terminalia argentea* presented the highest values for fiber length, fiber wall thickness and vessel element diameter. Wood of all three species were placed in class D40 of resistance of Brazilian native forest species according to ABNT NBR 7190-1 (ABNT, 2022).

Astronium urundeuva presented an average of 558 kg m^{-3} for basic density, a value slightly below the range of 600-650 kg m^{-3}, according to (IPT, 2024). *Astronium fraxinifolium* presented an average of 483 kg m^{-3} for basic density, a value below that observed by (IPT, 2024), and *Terminalia argentea* presented an average of 436 kg m^{-3}, a value below that found by (Nogueira et al., 2007).

For apparent density, *A. urundeuva* presented an average of 856 kg m^{-3}, a value below the range of 1000-1121 kg m^{-3}, according to (IPT, 2024) and (Faria et al., 2020). *Astronium fraxinifolium* has an average apparent density of 770 kg m^{-3}, a value within the range presented by (IPT, 2024), and *Terminalia argentea* had an average apparent density of 719 kg m^{-3}, a value similar to that observed by Paula and Costa (2011). These observed

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differences may be related to the 21-year-old wood evaluated and, therefore, most likely younger than the wood tested by (IPT, 2024). However, apparent density is a wood quality parameter that simultaneously reflects an association among chemical, anatomical, and physicomechanical characteristics, supporting the importance of its determination (Talgatti et al., 2018). By its complexity, wood density is a characteristic that varies between species and trees of the same species, both radially and longitudinally in the same tree and along age, depending on the spacing and location of plantings (Lima et al., 2021).

Due to the low average annual volumetric increase in wood volume of the species at 22 years of age, thinning could have been carried out at younger ages to obtain greater volumetric growth in the remaining trees. However, there is an inverse relationship between the average annual volumetric increase (Table 1) and wood densities (Figure 3a-b).

The three species evaluated here presented values of compressive strength greater than 40 MPa (*Astronium urundeuva* fc0 = 48MPa, *Astronium fraxinifolium* fc0 = 43.60 MPa, and *Terminalia argentea* fc0 = 43.61 MPa, respectively), placing these woods in resistance class D40 of native forest species according to ABNT NBR 7190-1 (ABNT, 2022). Based on the values of wood density and compression resistance, the woods of *Astronium urundeuva*, *Astronium fraxinifolium*, and *Terminalia argentea* have potential for industrial use at 22 years of age. They can be used for various purposes that do not have many structural application restrictions.

At the same time, however, the lower survival rate of *Terminalia argentea* resulted in greater growth in diameter and height in the remaining trees (Table 1). This natural phenomenon may explain, to some extent, the lower values of density and mechanical resistance of this species when compared to those properties in *Astronium urundeuva* and *Astronium fraxinifolium* (Figure 3). Several studies reporting on the effect of competition between trees on wood density have found that this increase is correlated with a lower rate of competition between trees (Vidaurre et al. 2018; Lima et al., 2022). Therefore, competition between trees can also influence wood density, a fact that foresters should recognize and incorporate into their management planning in order to adapt spacing in concordance with the final use of the wood (Moulin et al., 2020).The degree of competition between trees influences the intensity of juvenile/adult wood production, and it is desirable that the transition between juvenile and adult wood occur at younger ages, as this will result in a higher percentage of adult wood at the end of the seasonal cutting cycle (Moulin et al., 2020). It was found that age influences most of the mechanical properties of the wood from commercial plantations of the species *Schizolobium amazonicum*, with the base log showing the highest values of mechanical resistance (Vidaurre et al., 2018).

However, this greater growth of trees in forests, which, as noted, is promoted by a lower rate of competition, causes the formation of a greater amount of juvenile wood, which is, in turn, one of the factors that most contributes to the formation of lower density wood owing to the characteristics of juvenile wood in this growth phase (Lima et al., 2022).

We found wood properties to be correlated differently among the separate species (Figure 5). A direct relationship exists between wood density and resistance to compression parallel to the fibers, though it is of low intensity. Therefore, as density increases, modulus of elasticity and modulus of rupture intensely increase (Talgatti et al., 2018). In a study of correlations between different properties of *Ruizterania albiflora* wood, it was found that apparent density only showed significant correlations with modulus of elasticity in tension parallel to the fibers and modulus of elasticity in static bending (Soares et al., 2021).

In the regression analyses among properties, we found that the relationships between basic density and apparent density were the independent variables having the greatest impact on the dependent variables, *A. fraxinifolium* and *A. urundeuva*, for which the simple linear model best fits the data (Figure 5a-b).

In the present work, other models exhibited varying relationships between the variables, albeit with a lower representativeness rate, approximately 29 to 39% (Figures 5c-h). Since this represents only 29 to 39% of data variation between properties, only this percentage range can be explained by the equation for the model obtained, while the other 61 to 41% of data variation theoretically represents the residual variance. Therefore, these models are considered too precise for use in estimating these properties. However, Brazil has a large number of native tree species with potential for use in the timber industry; therefore, the existence of normative equations that correlate wood density with mechanical properties is very useful (Gomes et al., 2023). Regression models based on two parameters, compression resistance and static flexion, are more accurate in estimating shear strength for tropical species (Almeida et al., 2023).

For instance, the apparent density of *A. urundeuva* wood showed a negative correlation with ray height (Longui et al., 2017), which may also be related to the high concentration of tyloses in the pith and a higher content of extractives in the heartwood of *A. urundeuva*.

Using regression analysis to study the wood properties of several *Eucalyptus* species, good regression models were obtained to estimate mechanical properties, considering the height of the radii and the apparent density. Vessel elements and frequency had a significant negative correlation with tensile strength parallel to the fibers and with the modulus of elasticity in tensile strength parallel to the fibers. The width and height of the radii showed strong correlations with the apparent density and mechanical properties analyzed. Fiber characteristics also showed positive correlations with physic-mechanical properties (Marini et al., 2022).

Characterizing the quality of wood to ensure its optimal use is typically performed based on the species and the planting system. Understanding how species can benefit from each other in consortia is the key to multi-species forestry, which can bring significant gains in improving forest connectivity and restoring degraded landscapes, reconciling economic gains with conservation. Wood quality is defined as the degree of excellence relative to the intended application, but without the application of precise metrics. Nonetheless, it is possible to establish some parameters that align the quality of wood with its most appropriate use. We suggested that the studied wood from 22-year-old trees in a heterogeneous planting already presents wood quality suitable for use timber industry and can at the very least, be classified within a medium resistance class.

5. CONCLUSION

According to the results presented, only compressive strength parallel to the fibers does not differ significantly among the species. *Astronium urundeuva* presented the highest values for basic density and apparent density, and *Terminalia argentea* presented the highest values for fiber length, fiber wall thickness and vessel element diameter. The greater growth in diameter and height of *Terminalia argentea* trees caused lower wood density as a result of the lower rate of competition between trees of this species.

The best Pearson correlations were found for basic density and apparent density in both *Astronium fraxinifolium* and *Astronium urundeuva*. The best regression equations were obtained for the relationship between basic density and apparent density in *Astronium fraxinifolium* and *Astronium urundeuva*, with the simple linear model showing the best fit for the data. The relationship between apparent density and compressive strength in *Terminalia argentea*, however, had a lower representativeness rate.

The age of the studied trees is below that of wood usually sold for specific purposes; nevertheless, these tree species can still be placed in class D40 of resistance, similar to the species *Ocotea* sp., *Goupia glaba*, and *Vochysia* sp.

In general, it is noteworthy that, in the intercropping system, the species *Astronium fraxinifolium* and *Astronium urundeuva* showed similar behavior in relation to the properties of the wood studied. However, the species *Terminalia argentea* stood out for having a lower wood density compared to the other species. This can be attributed to the lower survival rate of this species, resulting in greater growth of the remaining trees selected for the assessment of wood properties, which, in turn, influenced wood density. Therefore, thinning operations could have been carried out to increase wood production; however, this may alter the density of the wood of the remaining trees.

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AUTHOR CONTRIBUTIONS

GHC, MR, AMS and JC: Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. MLMF, MLTM, ELL and ILL: Formal analysis, Methodology, Writing – review & editing.

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