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Articles

Technological properties of *Gmelina arborea* wood cultivated in Brazil

Propriedades tecnológicas da madeira de *Gmelina arborea* cultivada no Brasil

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ABSTRACT

The study aimed to characterize the wood of *Gmelina arborea*, cultivated in southern Brazil, by analyzing its anatomical, physical, chemical, and mechanical properties. Trees were felled, and disks were removed for analysis following the methods and recommendations outlined in the normative standards. Statistical analysis of the results was performed using analysis of variance (ANOVA – $p \leq 0.05$), Tukey's test ($p \leq 0.05$), and Pearson correlation between density and anatomical parameters. The results revealed that *G. arborea* wood has low basic density, is longitudinally homogeneous along the trunk, and is dimensionally stable. In terms of chemical composition, it demonstrated low energy potential in its natural condition but shows potential for use in pellet and briquette production, as well as suitability for cellulose production. The wood exhibits low strength and hardness, making it suitable for applications that do not require robust mechanical properties, such as non-structural uses, formwork, moldings, and objects that do not demand high mechanical strength. These findings have the potential to inform, guide, and promote the future cultivation of the species in Brazil, exploring its technological potential in specific applications.

Keywords: Anatomy; Physics; Chemistry; Mechanics; Wood quality

RESUMO

O estudo realizado teve como objetivo a caracterização da madeira da espécie *Gmelina arborea*, cultivada no Sul do Brasil, analisando suas propriedades anatômicas, físicas, químicas e mecânicas. Árvores foram derrubadas e discos foram retirados para análises, as quais seguiram os métodos e recomendações presentes nos padrões normativos. A análise estatística dos resultados foi realizada com análise de variância (ANOVA – p ≤ 0,05), teste Tukey (p ≤ 0,05) e correlação de Pearson entre a densidade e os parâmetros anatômicos. Os resultados revelaram que a madeira de *G. arborea* possui baixa densidade básica, sendo homogênea longitudinalmente ao longo do fuste e estável dimensionalmente. Quanto à composição química, demonstrou baixo potencial energético em condição natural, porém com possibilidade de ser utilizada na produção de péletes e briquetes, além de capacidade de exploração para a produção de celulose. A madeira apresenta baixa resistência e dureza, aconselhando seu uso em aplicações que não demandam características mecânicas robustas, como usos não estruturais, caixarias, molduras e objetos que não requisitam resistência mecânica. Essas descobertas têm o potencial de informar, orientar e fomentar futuros cultivos da espécie no Brasil, explorando seu potencial tecnológico em aplicações específicas.

Palavras-chave: Anatomia; Física; Química; Mecânica; Qualidade da madeira

1 INTRODUCTION

Wood is a lignocellulosic material with inherent variability at both cellular and macroscopic levels. Its characterization requires anatomical analysis, quantification of chemical compounds, and determination of physical and mechanical properties to assess potential applications.

Anatomical features not only enable species identification but also provide insights into wood structure and its relationship with various properties. These characteristics influence density, permeability, and mechanical strength (Evangelista *et al*., 2010), whereas the combined anatomical and physicochemical properties affect dimensional stability (Benin *et al*., 2017; Dias *et al*., 2017).

Chemical composition can vary within the same species depending on local growth conditions, including climate, soil type, and nutrient availability (Demirbas, 2002; Kumar *et al*., 2010). Wood strength, which reflects its ability to withstand applied loads, determines its performance in structural applications, with higher strength correlating to improved usability.

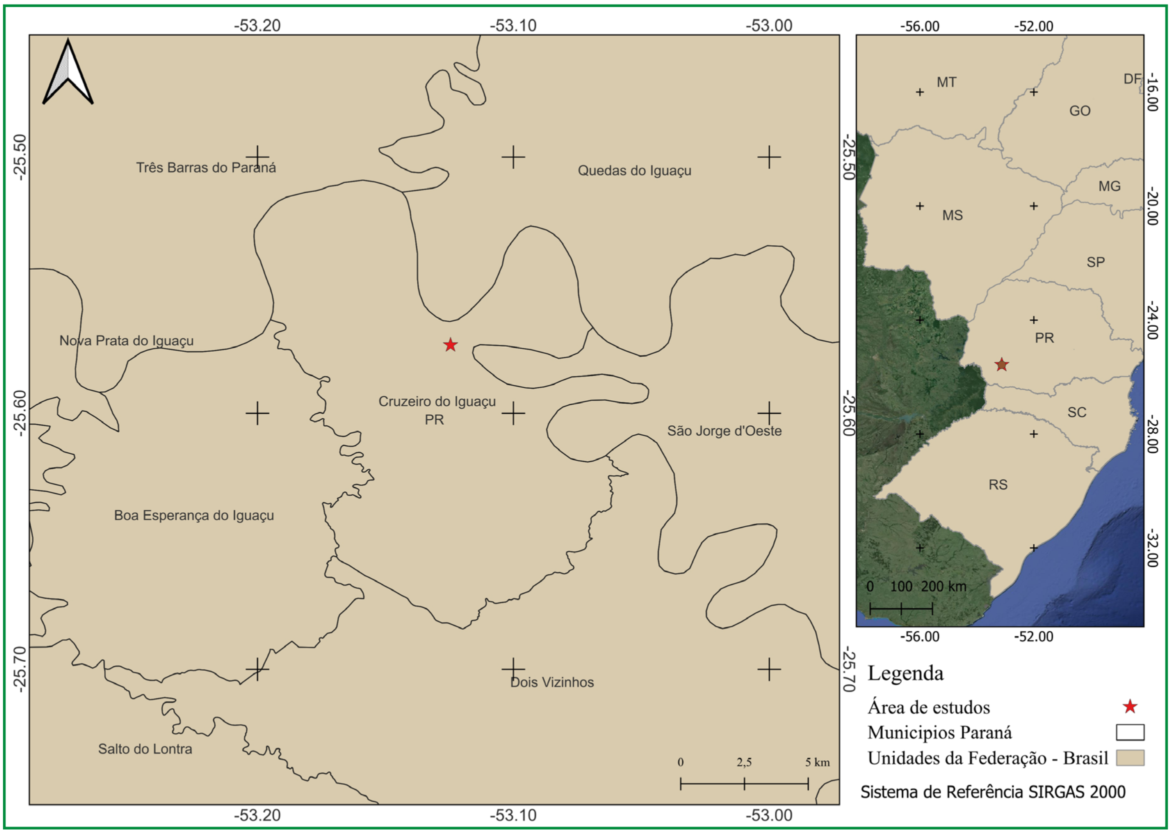
Understanding wood properties and composition is essential for optimizing its use, particularly in lesser-known species that may serve as alternatives to conventionally utilized woods. This is especially relevant for fast-growing species such as *Gmelina arborea*, which exhibits rapid growth (Mitchual *et al*., 2018), with an average annual volume increment of 0.0128 m³ at 25 years of age (Souza, 2018).

From this perspective, this study aims to characterize *Gmelina arborea* wood cultivated in southern Brazil by evaluating its anatomical, physical, chemical, and mechanical properties.

2 MATERIALS AND METHODS

Twenty-five-year-old trees, with an average diameter at breast height (DBH) of 24.5 cm and a commercial height of 9.4 m, were sourced from an experimental forest in Paraná, Brazil, established to diversify local species composition and assess the adaptation of *Gmelina arborea* (Figure 1).

Figure 1 – Location map of the plantation site



Source: Authors (2025)

From the selected trees, three 40-mm-thick disks were extracted at predetermined positions: the base, DBH, and commercial height. These disks were used to determine basic density along the stem, as well as anatomical and chemical properties. Logs from the base were processed into blocks for sample preparation, enabling the assessment of physical properties (apparent density and dimensional variation) and mechanical properties (static bending, Janka hardness, and parallel-to-grain compression).

2.1 Anatomical properties

From each disk, wedges were extracted and processed into three 1 cm^3 wood blocks, oriented radially from bark to pith. The samples were softened in water, sectioned using a microtome into 25-μm-thick slices, and stained with Astra blue and safranin. A sequential ethanol dehydration process followed, after which the sections (transverse, tangential, and radial) were mounted on glass slides with Entellan and coverslips.

Anatomical characterization and measurements followed IAWA (1989) guidelines, with adaptations from Coradin & Muñiz (1992). For each parameter, 25 measurements were performed to determine the mean and standard deviation of quantitative traits, including vessel frequency (mm^2), vessel diameter (μm), ray height and width (μm), and ray frequency (mm linear).

Fiber length (μm) and cell wall thickness (μm) were analyzed using samples collected radially from the bark to the pith. The samples were macerated in a solution of hydrogen peroxide and glacial acetic acid, incubated at 60°C for 24 hours, and subsequently mounted on slides for microscopic analysis.

For anatomical measurements, a Zeiss Discovery V12 stereomicroscope was used to capture and process images with AxionVision 4.7 software. Fiber length and width measurements were conducted using an Olympus CX-40 optical microscope equipped with an eyepiece micrometer scale.

2.2 Physical properties

Basic wood density (*Db*) was determined using two opposing wedges extracted from a disc at each sampling position per tree, totaling 36 wedges. After saturation, the wedges were weighed using a hydrostatic balance. The samples were then oven-dried, initially at 50±2°C and subsequently at 103±2°C, to obtain dry mass. The basic density was calculated based on the recorded data.

To determine apparent density at 12% moisture content (*Da*), 10 samples per tree were prepared, each measuring 25 × 25 × 100 mm, for a total of 60 samples. These samples were conditioned in a climate chamber at 20±2°C and 65±5% relative humidity until a constant mass was achieved. Their weights and volumes were then measured according to COPANT (Comisión Panamericana de Normas Técnicas) standard 461 (1972).

Dimensional variation analysis followed COPANT standard 462 (1972), using 10 samples per tree with nominal dimensions of 25 × 25 × 100 mm, properly oriented according to standard specifications.

2.3 Chemical properties

From the DBH disk of each tree, 1-cm-wide radial samples from the pith to the bark were collected and reduced to small wood chips. These chips were processed into sawdust using a Willey-type knife mill and subsequently sieved to obtain different particle sizes following TAPPI standard T 257 cm-02, then used for the following analyses: total extractives content (TAPPI T 204 cm-97), lignin content (TAPPI T 222 om-02), and ash content (TAPPI T 211 om-02). Fixed carbon content was calculated according to Equation (1).

$$\textit{Fixed carbon content}\ (\%) = (100 - (\textit{Ash content}\ (\%) + \textit{Volatiles}\ (\%)) \qquad (1)$$

Holocellulose content (*Hol*) was determined by subtracting the total extractives (*ET*), Klason lignin (*L*), and ash content (*TC*) from the total composition, considering 100% as the reference value.

2.4 Mechanical properties

Mechanical tests were conducted using samples obtained from the first log. After conditioning to achieve hygroscopic equilibrium (20±2°C temperature and 65±5% relative humidity), five specimens per tree were prepared for each mechanical property test, following COPANT standards 464/1972 (parallel-to-grain compression), 465/1972 (Janka hardness), and 555/1972 (static bending). Tests were performed using a universal testing machine (EMIC – DL 30.000), and the average results were expressed in the International System of Units (SI).

2.5 Statistical analysis

Prior to statistical analysis, the data were assessed for variance homogeneity (Bartlett and Hartley tests) and normality (Kolmogorov–Smirnov test). Analysis of variance (ANOVA, $p \leq 0.05$) was performed, and when significant differences were detected, Tukey's test ($p \leq 0.05$) was applied for comparison of means. Pearson correlation analysis was used to evaluate the relationship between density and anatomical parameters.

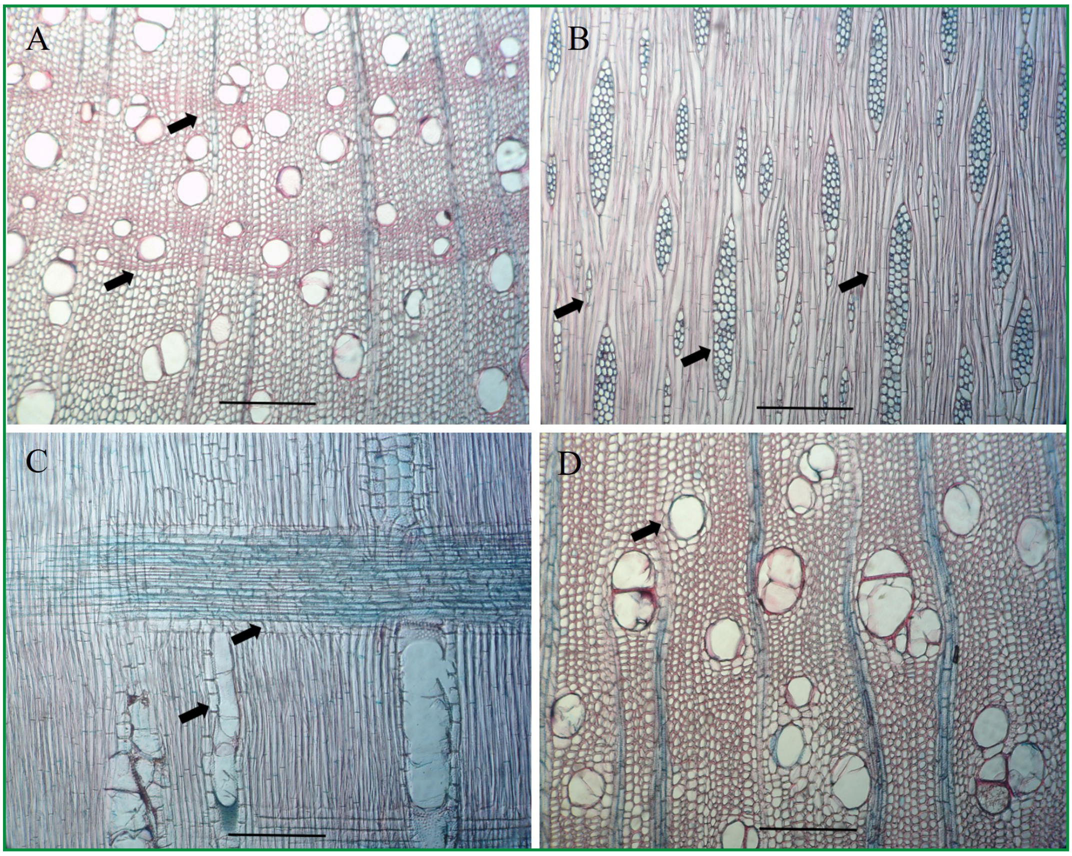
3 RESULTS AND DISCUSSIONS

3.1 Anatomical characterization

The wood exhibits distinct growth rings, a color difference between heartwood and sapwood, and an irregular interlocked grain. It has a diffuse porosity with solitary and multiple vessels (Figure 2A).

The tangential lumen diameter of vessels ranges from 100 to 200 µm, with minimal tyloses formation. Fibers have an average length between 900 and 1600 µm, a wall thickness of 4.09 µm, and the presence of septa (Figure 2B). Rays are heterogeneous, consisting of procumbent cells in the central region and square cells at the extremities (Figure 2C). Axial parenchyma is scarce paratracheal to abundant vasicentric (Figure 2D), with a predominance of multiseriate rays three to five cells wide (Figure 2B). Vessel diameter and frequency were measured at different axial positions (Table 1).

Figure 2 – Anatomical images of the wood of *G. arborea*



Source: Authors (2025)

In where: A – Transverse section showing growth rings; B - Tangential section with uniseriate and multiseriate rays; C - Radial section indicating ray cell types and axial parenchyma associated with vessels; D - Transverse section highlighting the vasicentric parenchyma. Scale: 250 µm.

Table 1 – Quantitative vessel characteristics of *G. arborea* wood at three axial positions

Position	Vessel diameter (µm)		Vessel frequency (n°/mm²)	
	Mean value	C.V. (%)	Mean value	C.V. (%)
Base	133.71 b	40.10	7.76 a	48.16
DBH	156.68 a	33.93	7.08 a	27.35
Top	162.32 a	24.89	5.85 b	34.36
Overall mean	150.90	33.64	6.90	40.52

Source: Authors (2025)

In where: Different letters in the same column indicate a statistical difference by the Tukey test (95% probability); C.V.: Coefficient of variation.

The smallest vessel diameters were observed at the base, significantly differing from the other positions. The lowest vessel frequency was found at the top of the commercial height, which also differed from the other positions.

The relationship between vessel diameter and frequency is directly linked to both plant physiology and wood properties. A high frequency of large-diameter vessels results in increased permeability and reduced mechanical strength due to the lower proportion of woody material relative to porous spaces.

The tangential lumen diameter of vessels ranges from 100 to 200 μm, classifying *G. arborea* as a medium-textured species according to IAWA (1989) (Zenid & Ceccantini, 2012). Moya & Tomazello (2008), analyzing trees aged 9 to 12 years, reported larger average vessel diameters (189 μm) but lower vessel frequency, ranging from 3 to 6 rays/mm².

The anatomical variations observed are attributed to factors such as tree age and environmental conditions influencing growth, including precipitation and soil nutrient availability. Ray width decreases with height along the tree, while ray frequency remains stable (Table 2).

Table 2 – Quantitative characteristics of rays in *G. arborea* wood at three axial positions

Position	Ray Height (μm)		Ray Width (μm)		Ray Frequency (n°/mm)	
	Mean	C.V. (%)	Mean	C.V. (%)	Mean	C.V. (%)
Base	351.89 a	37.76	70.88 a	21.13	4 a	29.24
DBH	294.55 b	34.34	65.77 a	28.48	4 a	34.12
Top	319.62 ab	33.73	57.29 b	20.18	4 a	25.93
Overall mean	322.01	36.22	64.65	25.21	4	29.93

Source: Authors (2025)

In where: Different letters in the same column indicate a statistical difference by the Tukey test (95% probability); C.V.: Coefficient of variation.

Ray height follows a pattern similar to that observed in basic density (Table 3), increasing from the base to breast height (DBH) and decreasing from DBH to the top, with a positive correlation between these variables (r = 0.8273).

Table 3 – Pearson correlation coefficient (r) between basic density (Db) and anatomical parameters of *G. arborea* wood

	Db	Vessel diameter (µm)	Vessel frequency (n°/mm²)	Ray height (µm)	Ray width (µm)	Ray frequency (n°/mm)
Db	1					
Vessel diameter (µm)	-0.3296	1				
Vessel frequency (n°/mm²)	-0.1639	-0.8773	1			
Ray height (µm)	0.8273	-0.8031	0.4186	1		
Ray width (µm)	-0.1424	-0.8876	0.9998	0.4383	1	
Ray frequency (n°/mm)	-0.8663	-0.1860	0.6347	-0.4361	0.6178	1

Source: Authors (2025)

The other anatomical parameters showed a negative correlation, with particular emphasis on ray frequency (r = -0.8663), meaning that as ray frequency increases, basic density decreases. This analysis is also relevant for vessel diameter, vessel frequency, and ray width. Based on the fiber length of the species, which increases radially, combined with the reduction in lumen diameter and the increase in wall thickness radially, it is inferred that the wood under study is juvenile, meaning that its growth has not yet stabilized (Table 4).

Table 4 – Quantitative characteristics of *G. arborea* wood fibers at three radial positions

Position	Length (µm)		Lumen diameter (µm)		Wall thickness (µm)	
	Mean	C.V. (%)	Mean	C.V. (%)	Mean	C.V. (%)
Pith	811.11 a	19.46	31.40 a	19.79	3.74 a	30.71
Intermediate	1098.33 b	13.11	30.13 ab	21.39	3.93 a	29.60
Bark	1417.22 c	17.19	29.08 b	22.73	4.61 b	29.48
Overall mean	1108.89	27.98	30.20	21.43	4.09	31.26

Source: Authors (2025)

In where: Different letters in the same column indicate a statistical difference by the Tukey test (95% probability); C.V.: Coefficient of variation.

The presence of juvenile wood is common, as the formation of mature wood begins earlier in some species, while in others, juvenile wood persists for several years (Alfonso *et al*., 2010). This is the case with *G. arborea*, which has undergone few silvicultural interventions, and whose growth is influenced by edaphoclimatic conditions.

Lumen diameter is directly related to fiber wall thickness, with an inverse proportionality. In other words, when lumen diameter decreases and wall thickness increases, there are fewer empty spaces. Consequently, wood density and mechanical resistance increase.

Although lumen diameter and fiber cell wall thickness are considered the most influential characteristics in wood density, other factors, such as the frequency and thickness of parenchyma cell walls, as well as vessel frequency and size, also influence not only density but also other properties such as permeability and mechanical strength.

The fiber values align with those reported by Moya & Tomazello (2008), who documented thin-walled fibers (4.56 μm), a lumen diameter of 35.25 μm, and a length of 1020 μm. The average fiber cell wall thickness (4.09 μm) is similar to that of medium basic density eucalyptus species, such as *Eucalyptus obliqua* (3.6 μm), *E. pilularis* (4.1 μm), and *E. marginata* (3.9 μm), but differs from high basic density species like *Corymbia citriodora*, which has an average wall thickness of 6.1 μm (Redman *et al*., 2016).

3.2 Physical properties

The average basic density (Db) was 380 kg.m³ (Table 5), classifying the wood as low-density (IAWA, 1989), which implies lower mechanical resistance compared to higher-density species (Welter *et al*., 2024).

Table 5 – Basic density at three positions along the trunk and apparent density (12%) of *G. arborea* wood

Density	Mean (kg.m-³)	Standard deviation	Coefficient of variation (%)
Basic (Db) - Base	380	0.0254	6.63
Basic (Db) - DBH	370	0.0157	4.29
Basic (Db) - Top	380	0.0433	11.28
Basic (Db) - Mean	380	0.0329	8.16
Apparent (Da) – Mean	450	0.0327	7.29

Source: Authors (2025)

The variation along the trunk is considered minimal, indicating axially homogeneous wood, an important characteristic for industrial applications. This minimal base-to-top density variability was also observed by Espinoza (2004). However, the observed Db, classified as low, limits the applications of this species in situations requiring high strength, such as structural use. Therefore, its application is mainly recommended for non-load-bearing components.

The apparent density at 12% moisture content averaged 450 kg.m³, consistent with previous studies on young *G. arborea* wood from commercial plantations (Piotto *et al*., 2003; Dvorak, 2004; Vallejos *et al*., 2015; Moya *et al*., 2017). In an experimental forest in the coastal region of Paraná, managed under a coppice system, Marcene *et al*. (2006) reported an average density of 580 kg.m³ for materials of varying ages (4 to 12 years). Variations in properties may be related to site conditions and planting density (Modes *et al*., 2022).

Based on this property, the wood is recommended for furniture and light construction (Onyekwelu & Stimm, 2002), as well as for pulp production, medium-density fiberboard, laminated panels, wood-cement composites, particleboard, plywood, doors, moldings, pencils, and matchsticks (Dvorak, 2004).

Regarding dimensional variation parameters, the volumetric retraction of 10.90%, along with a low anisotropic factor (1.38), indicates that the wood has good dimensional stability (Table 6).

Table 6 – Average dimensional variation values for *G. arborea* wood

Parameter	Total wood retraction (%)	
	Mean	**Coefficient of variation (%)**
Axial	0.07	77.86
Radial	4.55	10.58
Tangential	6.27	10.43
Volumetric	10.90	9.77
Anisotropic factor	1.38	8.20

Source: Authors (2025)

The anisotropic factor value closest to unity (1) indicates greater stability, as it reduces the anisotropic nature of the wood, favoring its use in the manufacturing of products where minimal dimensional instability is required, such as furniture production. This is due to the proximity of tangential and radial retraction values, both of which are considered low.

The axial retraction of *G. arborea* wood can be considered normal, according to Kollmann & Côté (1968), who state that the total longitudinal retraction of normal wood ranges between 0.1% and 0.9%.

The different dimensional changes across the wood planes are attributed to the characteristics of their anatomical and chemical structures. As reported by Kollmann & Côté (1968) and Oliveira *et al*. (2010), hardwood species exhibit varying ray height and width, and the greater the number of these cells, the higher the likelihood of restricting dimensional change in the radial direction. The radial dimensions of the fibers, as well as the chemical differences between the radial and tangential cell walls, also influence variations across the wood's anatomical planes (Masserann & Mariaux, 1985).

The relationship between density and the other evaluated physical properties was weak and did not follow a consistent positive or negative correlation trend, making it impossible to associate the retraction behavior of *G. arborea* wood with its basic and apparent density (Table 7).

Table 7 – Pearson correlation coefficient (r) between basic and apparent density and retraction parameters of *G. arborea* wood

	Db	**Da**	**Tangential R**	**Radial R**	**Axial R**	**Vol R**	**FA**
Db	1						
Da	0.9763	1					
Tangential R	-0.2801	-0.1690	1				
Radial R	-0.2494	-0.1985	0.7570	1			
Axial R	0.0966	0.0782	-0.0286	-0.0816	1		
Vol R	-0.2798	-0.1894	0.9554	0.9130	-0.0009	1	
FA	-0.0448	0.0326	0.2520	-0.4304	0.0526	-0.0368	1

Source: Authors (2025)

In where: Db: Basic density; Da: Apparent density (12%); R: Retraction; vol: volumetric; FA: Anisotropic factor.

These results align with those obtained by Dias *et al*. (2017) and indicate that analyzing the relationships between properties is essential for assessing wood quality. That is, determining an isolated characteristic may lead to misinterpretations and incorrect applications of the wood.

3.3 Chemical properties

The proximate chemical analysis and the chemical component contents of *G. arborea* wood (Table 8) reveal that the ash and lignin contents were higher than those reported in the literature (Moya-Roque & Tenorio, 2013; Moya-Roque *et al*., 2018). In contrast, the total extractives content was lower than that found by these authors; however, it is still considered low. The extractives content is associated with heartwood formation and can influence resistance to liquid flow and tyloses formation. However, few tyloses formations were observed in the anatomical analysis. Consequently, lower extractives content results in higher wood permeability, which facilitates drying and treatment processes.

Table 8 – Contents (%) of ash, volatiles, fixed carbon, total extractives, lignin, and holocellulose in *G. arborea* wood

	Ash	Volatiles	Fixed carbon	Total extractives	Lignin	Holocellulose
Mean (%)	1.43	92.10	6.47	6.20	28.94	63.42
C.V. (%)	8.43	2.05	29.98	9.64	6.71	3.22
S.D.	0.12	1.89	1.94	0.60	1.94	2.04

Source: Authors (2025)

In where: C.V.: Coefficient of variation; S.D.: Standard deviation.

The ash content was higher, and the fixed carbon content was lower than those of commonly used woods for energy generation in Brazil, such as some *Eucalyptus sp.* genetic materials (Brun *et al*., 2018; Zanuncio *et al*., 2019). The holocellulose and lignin contents were similar to those reported in the literature (Zanuncio *et al*., 2014; Juizo *et al*., 2018) when analyzing eucalyptus wood, which is widely used in pulping processes.

Additionally, the lignin content was comparable to that reported by Castro *et al*. (1979) when evaluating *G. arborea* for cellulose extraction.

Based on these findings, it can be inferred that this species has a low fuel capacity, compromising its energy potential when required, with ash and fixed carbon content being the primary limiting factors. However, it is suggested that this species could be used in the production of pellets and briquettes, mitigating the impact of its low wood density. Furthermore, the species shows potential for the pulp and paper industry, as low extractives and lignin content positively affect pulp production and yield, corroborating Ramos *et al*. (2024).

3.4 Mechanical properties

The analysis of the average values of mechanical characterization (Table 9) reveals that *G. arborea* wood falls into class C20, which is the lowest classification (ABNT, 1997).

Table 9 – Mean values of mechanical properties of G. arborea wood obtained at 12% moisture

Mechanical Property of the Wood		Mean	Standard Deviation	C.V. (%)
Compression parallel to the fibers	Fc0 (MPa)	27.32	3.39	12.40
	Ec0 (MPa)	6428.83	1666.98	25.93
Static bending	FM (MPa)	62.67	3.00	4.79
	EM0 (MPa)	7832.69	448.51	5.73
Axial Janka Hardness	FH0 (N)	2582.61	475.28	17.43
Radial Janka Hardness	FH R (N)	2048.48	447.80	21.86
Tangential Janka Hardness	FH T (N)	2236.69	450.05	21.25

Source: Authors (2025)

In where: Fc0 = compressive strength parallel to the fibers; Ec0 = modulus of elasticity obtained from the parallel-to-fiber compression test; FM = static bending strength; EM0 = modulus of elasticity obtained from the static bending test; FH0 = wood hardness in the parallel-to-fiber direction, measured by the Janka method; FH R = wood hardness in the radial direction, measured by the Janka method; FH T = wood hardness in the tangential direction, measured by the Janka method. C.V. (%) = coefficient of variation.

For Janka hardness, the axial direction showed a higher value than the other wood orientations due to the arrangement of structural wood cells, which are primarily distributed longitudinally. However, the values for all orientations—axial, radial, and tangential—align with those reported by Gonzáles-Trejos & Serrano-Montero (2004), ranging from 1980 to 3206 N.

Among the evaluated mechanical properties, only the modulus of elasticity in compression parallel to the fibers (Ec0) was higher than that reported by Müller *et al*. (2014) for *E. benthamii* wood, a species planted in southern Brazil. Compared to Amazonian species studied by Cardoso *et al*. (2012), the mechanical properties of *G. arborea* are slightly lower. However, these cited species have higher apparent density values.

Similarly, the mechanical properties of *G. arborea* are lower when compared to those of tropical pines (*Pinus caribaea var. bahamensis, P. caribaea var. caribaea, P. caribaea var. hondurensis, P. chiapensis, P. maximinoi, P. oocarpa, P. tecunumanii,* and *P. taeda*), as evaluated by Trianoski *et al*. (2014). These pine species had an apparent density (12%) ranging between 0.43 and 0.57 g.cm³. It is noteworthy that *G. arborea* has a lower density than all species mentioned in the literature, which, combined with its juvenile wood, results in lower mechanical properties when compared to the cited references.

Given this, the recommended uses for *G. arborea* wood include light construction, baseboards, ceilings, paneling, and raw material for small wooden objects such as supports, picture frames, handicrafts, and formwork—applications that do not require mechanical strength. The species also has potential for wood densification processes and preservative treatments.

3 CONCLUSIONS

G. arborea wood has a low basic density, is longitudinally homogeneous, and dimensionally stable.

Its chemical composition indicates low natural energy potential; however, it shows promise for pellet and briquette production.

The wood has low strength and hardness, making it unsuitable for applications that require high mechanical performance, such as structural uses. However, it is well-suited for non-structural applications and a variety of wooden objects, including supports, frames, artisanal pieces, formwork, and small to medium-sized household items.

Ultimately, the species demonstrates versatility for different applications. Based on the aforementioned information, new cultivation strategies could be explored to harness its technological potential.

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