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Correlations among select properties and anatomical parameters of *Dipteryx odorata* wood

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ABSTRACT

The increasing demand for sustainable and high-performance materials in civil engineering highlights the importance of understanding the relationship between wood anatomy and its mechanical behavior. This study aims to evaluate correlations between anatomical parameters and mechanical properties of Cumaru (*Dipteryx odorata*), with the goal of improving its classification and structural application potential. Microscopy techniques were used to analyze key anatomical features, including fiber length, wall thickness, and vessel diameter, while mechanical tests were performed in accordance with Code NBR 7190-3:2022 to determine strength and stiffness parameters. Statistical analysis was applied to identify significant correlations between anatomical traits and physical-mechanical properties. Results demonstrate that anatomical parameters, together with apparent density, are reliable predictors of mechanical performance, particularly influencing modulus of elasticity and modulus of rupture. These findings confirm that anatomical analysis can complement traditional mechanical testing, enabling more efficient and non-destructive approaches for assessing wood quality. The study provides practical insights for selection, classification, and optimized utilization of Cumaru in engineering and construction, reinforcing its relevance as a sustainable structural material.

Keywords: Wood anatomy; Mechanical properties; Apparent density; Microscopy analysis.

1. INTRODUCTION

Currently, wood use is becoming increasingly prevalent in various applications, including furniture production, packing, energy generation, and, most notably, in construction [1–4]. In an era of significant climate change, productive sectors have a responsibility to source certified raw materials that enhance forest value and contribute to reducing greenhouse gases [5, 6].

In Brazil, wood in construction is characterized by its numerous applications, as structural elements (beams, columns, trusses, frames) [7–9], temporary uses (formwork, scaffolding), and building components (moldings, doors, floors, ceilings, partitions) [10–13]. This extensive variety of wood applications is attributed to factors such as ease of procurement, sustainability (legally sourced wood), high strength-to-weight ratio compared to steel and concrete, low energy consumption for processing, ease of manual and mechanical processing, and excellent thermal insulation properties [14–17].

Tropical forests of Amazon region form a complex system with a highly diverse distribution of timber species. However, their effective utilization requires properties knowledge to ensure rational and sustainable behavior in high-value products [18].

To properly use wood as structural systems, it is crucial to understand its physical and mechanical properties. Brazilian NBR 7190:2022 "Design of Timber Structures", by Brazilian Association of Technical Codes (ABNT) and North American D143:2022, by American Society of Testing and Materials (ASTM) consider, among mechanical properties, strength in compression parallel to grain as particularly important [19].

Since obtaining wood mechanical properties requires large-scale equipment typically found only in major research centers, ABNT NBR 7190-3:2022 [20] establishes relations between strength properties based on the characteristic value of strength in compression parallel to grain. Research considering density as estimator for

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strength and stiffness properties has been developed [21–24]. Results found in current literature show that only density is not sufficient to perform good estimative of such properties.

Wood species complete characterization, for structural purposes, requires about 540 determinations, encompassing physical and mechanical properties. This process is time-consuming and resource-intensive due to high cost of necessary equipment and tests duration. Recent studies have focused on reducing this workload by proposing methods that use estimates based on more easily obtained properties, such as apparent density, or taking in account correlation between properties [25–27].

With technological advancements, microscopic techniques use has significantly contributed to characterizing material basic structures. Various studies aim to this matter [28–30]. However, to date, few studies have considered anatomical parameters of tropical woods as estimates for mechanical properties.

The significance of this study lies in demonstrating the predictive potential of anatomical parameters and apparent density for assessing mechanical performance of Cumaru wood (*Dipteryx odorata*). By establishing correlations between anatomical features and mechanical properties, this research provides a scientific basis for developing non-destructive approaches to wood evaluation. Such methods can complement conventional testing, reduce costs and material waste while improve efficiency in the selection and classification of structural timber.

Furthermore, the findings contribute to advancing sustainable construction practices by optimizing the utilization of Cumaru, a high-density tropical species with considerable potential for structural applications. The innovative integration of anatomical analysis with mechanical testing reinforces the relevance of this approach for both scientific research and engineering practice, offering practical tools for enhancing material performance, structural reliability, and resource efficiency.

Furthermore, this study proposed evaluating potential interdependence among anatomical parameters (fiber, vessels and rays).

According to Brazilian Society of Silviculture [31], the lack of consistent information on technological properties and performance of Amazonian forest species under various conditions restricts their industrial potential.

2. MATERIALS AND METHODS

2.1. Materials

Cumaru wood (*Dipteryx odorata*) referred to in this research comes from South of Roraima State, Brazil. Batches of twelve beams between 4 and 4.5 meters long were obtained from trees over 50 years old.

From Cumaru wood, 12 specimens were obtained to tests, according to ABNT NBR 7190-3:2022 [20]. For anatomical parameters analysis, wood specimens were oriented according to three anatomical axes (longitudinal, radial and tangential).

For microscopic analysis, twelve histological slides were prepared, four oriented radially, four longitudinally and four tangentially. Furthermore, eight slides with macerated material were prepared specifically for analysis of anatomical parameters.

2.2. Methods

2.2.1. Determination of apparent density and shrinkage

Apparent density (ρ_{ap}) is a conventional specific mass, defined as mass to volume ratio of test specimens with a moisture content 12%, calculated by Equation 1.

$$\rho_{ap} = \frac{m_{12}}{V_{12}} \tag{1}$$

Where

m_{12} is the mass of the test specimen with 12% moisture content, expressed in kilograms (kg);

V_{12} is the volume of the test specimen with 12% moisture content, expressed in cubic meters (m^3).

Cross-sectional dimensions were measured with a caliper (accurate to 0.1 mm), and mass was recorded using an analytical balance (accurate to 0.01 g).

Specific deformation of shrinkage (ε_r) was determined, according to Brazilian document [20], in radial (R) and tangential (T) directions, as verified by Equation 2.

$$\varepsilon_r = \left(\frac{L_{i,sat} - L_{i,dry}}{L_{i,sat}} \right) \times 100 \quad (2)$$

Where

$L_{i,\,sat}$ is the linear dimension at equal or superior moisture of fiber saturation point;

$L_{i,\,dry}$ is the linear dimension at 0% moisture.

2.2.2. Mechanical testing

Mechanical tests for Cumaru species were conducted in accordance with guidelines of Brazilian Code NBR 7190-3:2022 [20]. Tests were performed using a Universal Testing Machine AMSLER, with load capacity 250 kN. The following properties were evaluated: compressive strength parallel to the grain (f_{c0}) and modulus of elasticity in compression parallel to the grain (E_{c0}); shear strength parallel to the grain (f_{v0}); radial shrinkage (RS) and tangential shrinkage (TS); tensile strength parallel to the grain (f_{t0}) and modulus of elasticity in tension parallel to the grain (E_{t0}); in addition to tensile strength perpendicular to the grain (f_{t90}). It is important to mention that the obtained results were adjusted to the standard moisture content of NBR 7190:200-1 [32], using the expressions provided in section 5.6.1 of the referred standard.

2.2.3. Microscopy analysis

Microscopy measurements included fibers (length, wall thickness, and diameter), vessel elements (frequency and diameter), and rays (height and width). Measurements were conducted in accordance with ABNT NBR 15066 [33] and International Association of Wood Anatomists (IAWA) [34] Codes.

To measure fibers individual characteristics (length, diameter, and wall thickness), microscope slides were produced using macerated material. Small fragments of Cumaru wood (30 to 40 chips) were removed from each sample and subjected to maceration process using Franklin's method [35, 36].

Macerated fragments were placed in Erlenmeyer flasks, and glacial acetic acid and hydrogen peroxide were added in a 1:1 ratio to cover the fragments. The flasks were then covered and placed in an oven at 50°C for 24 hours, a method used by MARINI *et al.* [37], MARINI *et al.* [38]. After maceration, fiber samples were washed three times with distilled water after the period in oven. Subsequently, a 1% aqueous solution of safranin dye was added.

An appropriate amount of material was then placed on a microscope slide and covered with another slide, ensuring no air bubbles were present. Using the prepared macerated material, measurements were carried out to verify fibers characteristics of Cumaru using an optical microscope (Olympus EX51 model).

Fibers wall thickness was calculated from data collected on fiber length and lumen diameter using Equation 3 [33].

$$T_{wf} = \frac{Wf - Dl}{2} \quad (3)$$

Where

T_{wf} is the wall thickness (mm);

W_f is the fiber length (mm);

D_l is the lumen diameter (mm).

Specimens were prepared in standardized dimensions (1 cm × 1 cm × 1 cm) and underwent a softening process by boiling in water. Subsequently, they were sectioned using a blade microtome to obtain histological slides with thicknesses ranging from 18 to 20 µm, in the three anatomical planes. These slides were identified and stored for microscopic analysis. Digital images were then collected from each slide using a microscope to measure samples anatomical features.

2.2.4. Statistical analysis

For Cumaru anatomical characterization, a total of twelve experimental determinations were performed for each anatomical parameter analyzed. The same number of determinations was also conducted for physical and mechanical properties. These analyses included determination of apparent density, dimensional stability (radial and tangential shrinkage), and mechanical performance (strength and modulus of elasticity in compression, shear, and tension parallel and perpendicular to grain).

As the number of determinations per property (anatomical, physical, mechanical) varies, statistical analyses were conducted using average values. After this verification, Pearson correlation coefficient (Pearson r: $-1 \leq r \leq 1$) was evaluated using analysis of variance (ANOVA at 5% significance). This coefficient was used to analyze relationships among anatomical properties, and between anatomical parameters, and physical and mechanical properties of Cumaru.

3. RESULTS AND DISCUSSION

Table 1 showed a synthesis of mean results of mechanical properties of Cumaru species. These values are in accordance with the prescriptions of ABNT NBR 7190-3:2022 [20].

Table 1: Synthesis of physical and mechanical properties of Cumaru.

SPECIES		$\rho_{ap,12}$ g/cm	RS %	TS %	f_{c0} MPa	f_{t0} MPa	f_{t90} MPa	f_{v0} MPa	E_{c0} MPa	E_{t0} MPa
Cumaru	Mean	1.09	3.95	6.38	93	122	2.85	17.84	23,002	22,119
	CV%	3.08	20.85	16.94	5.45	20.54	19.71	16.69	10.94	8.91

Apparent density of Cumaru wood found in this study was similar to that found by other authors [39]. Mechanical properties obtained for the Cumaru batch in this study are within the range of values reported in previous studies [40].

Characteristic strength values ($f_{w,k}$) of Cumaru in this study are presented in Table 2 and categorized according to strength classes of tropical wood group (CR), as prescribed by ABNT NBR 7190-3:2022 [20], which include:

Table 2: Characteristic values of strength ($f_{w,k}$) of Cumaru.

SPECIES	$f_{c0,k}$ MPa	$f_{t0,k}$ MPa	$f_{t90,k}$ MPa	$f_{v0,k}$ MPa	CR
Cumaru	96.29	93.37	3.67	14.82	D60

$f_{c0,k}$: Characteristic value of compression parallel to the grain; $f_{t0,k}$: Characteristic value of tension parallel to the grain; $f_{t90,k}$: Characteristic value of tension parallel to the grain; $f_{v0,k}$: Characteristic value of shear stress perpendicular to the grain; CR: Strength class.

Cumaru wood exhibited high strength values, Table 2, making it suitable for structural applications. Characteristic value in this study resulted in the higher strength class according to Code [20].

Table 3 presents a synthesis of results for anatomical characteristics of Cumaru, whose parameters, statistically evaluated by coefficient of variation (CV).

Table 3: Synthesis of anatomical properties of Cumaru.

SPECIES		Dv mm	Frv VESSEL/mm²	Hr mm	Wr mm	Lf mm	Df mm	Dl mm	Twf mm
Cumaru	Mean	0.14451	4.42155	0.15361	1.06822	1.11236	0.01400	0.00816	0.00277
	CV%	16.77	14.58	10.70	18.77	17.60	20.24	35.30	31.40

Vessel elements are depicted in Figures 1(a) and 1(b) for better illustrating the paper's aim. Mean tangential diameter was 0.14 mm. The mean of ray height 0.15 mm (Figures 1(c) and 1(d)). However, rays were quite wide, with a mean 1.07 mm.

Regarding the fibers, their diameters were classified as narrow, with average 0.01 mm [41]. Figure 2(a). In terms of length, short fibers predominated, measuring 1.11 mm, Figure 2(b). Lumen diameter was narrow, measuring 0.008 mm, Figure 2(c). Fiber wall thicknesses were moderate, with a measurement 0.002 mm, Figure 2(d) [37].

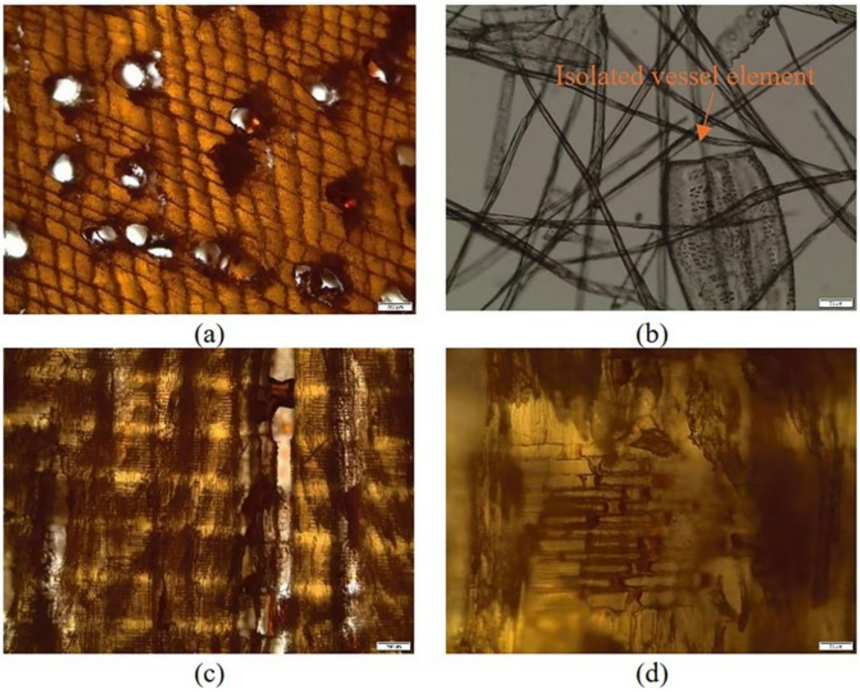

Figure 1: Transversal plane of: (a) vessel elements of Cumaru, (b) isolated vessel element of Cumaru, (c) tangential plane and (d) radial plane.

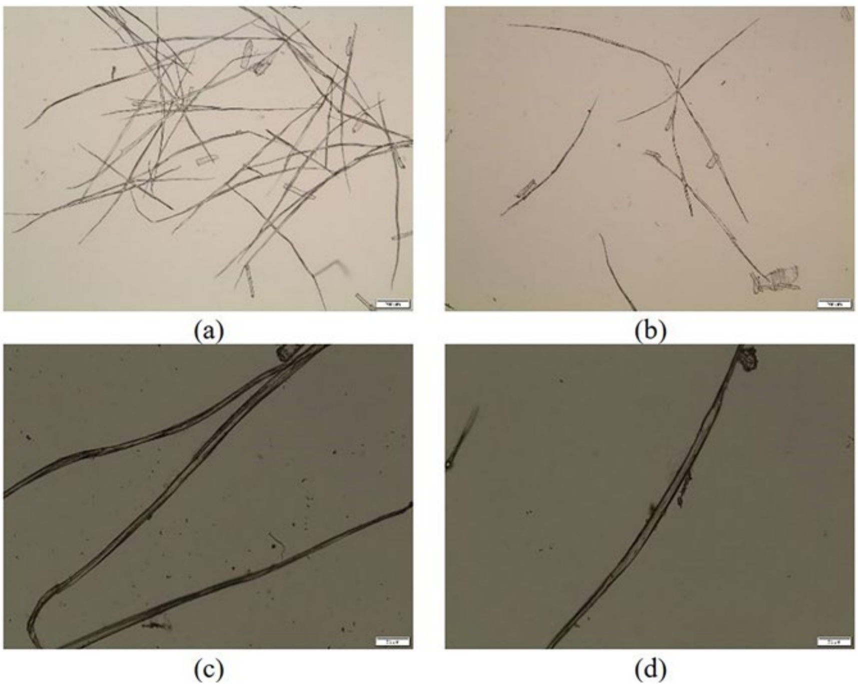

Figure 2: Fiber elements of Cumaru: (a) fibers diameter (Df); (b) fibers length (Lf); (c) lumens diameter (Dl); and (d) fiber wall thickness (Twf).

Table 4 elucidated results of Pearson test (Pearson's r) for correlations between the seven anatomical parameters evaluated for Cumaru.

According to Table 4, when relating Dv with the other anatomical variables, a significant correlation was found only with Hr. This correlation is negative, indicating that increases in one variable result in decreases in the other. Twf showed significant correlation with two other anatomical properties: Df and Dl [42].

Table 4: Results of the Pearson correlation test (–1 ≤ r ≤ 1) between anatomical properties.

STAT.	Dv	Frv	Hr	Wr	Lf	Df	Dl
Frv	–0.415						
Hr	0.275	0.038					
Wr	–0.240	–0.167	–0.126				
Lf	–0.284	–0.407	–0.112	–0.005			
Df	0.029	–0.062	0.373	0.050	–0.359		
Dl	–0.185	0.337	0.287	0.071	–0.474	0.884	
Twf	0.206	–0.390	0.378	0.023	–0.197	0.918	0.627

*At the 5% significance level, Pearson correlations considered significant by analysis of variance (ANOVA) are under-lined.

Table 5: Results of Pearson correlation test (–1 ≤ r ≤ 1) among anatomical parameters and physical and mechanical properties evaluated.

STAT.	$\rho_{ap,12}$	RS	TS	f_{c0}	f_{t0}	f_{t90}	f_{v0}	E_{c0}	E_{t0}
Dv	0.061	–0.195	0.288	–0.105	0.069	–0.232	0.004	0.289	–0.459
Frv	–0.303	0.386	–0.022	0.142	0.146	0.348	–0.082	0.219	0.035
Hr	0.227	–0.035	0.323	0.194	0.379	–0.204	0.159	0.156	0.053
Wr	0.443	–0.045	–0.039	0.408	–0.000	0.312	–0.117	0.088	0.213
Lf	0.141	–0.729	–0.642	–0.645	–0.358	–0.170	–0.091	–0.480	0.334
Df	–0.297	0.659	0.712	0.480	–0.003	0.316	–0.132	0.003	0.372
Dl	–0.409	0.754	0.619	0.526	0.127	0.577	–0.038	0.008	0.377
Twf	–0.149	0.461	0.662	0.355	–0.114	0.038	–0.188	–0.002	0.302

At the 5% significance level, Pearson correlations considered significant by analysis of variance (ANOVA) are underlined.

These findings highlight how specific wood anatomical features are interrelated, providing insights into its structural composition and potential performance characteristics in practical applications.

It's possible to observe that some parameters present insignificant influence to mechanical properties estimation. However, DI and Twf are the most important ones to – together with apparent density – increase accuracy of the cited estimation.

Table 5 displays results of correlation analysis among anatomical parameters and physical-mechanical properties of Cumaru species.

The strongest significant positive correlation observed is between Dl and RS, coefficient 0.754. Additionally, fibers lumen diameter showed another significant correlation with TS, coefficient of 0.619. Another positive correlation is between DI and f_{t90}, coefficient 0.577.

Df shows a significant positive correlation with RS, value 0.659; and with TS, value 0.712. The significant positive correlation between Df and RS and TS, suggests that as fiber diameter increases, wood tendency to shrink in both radial and tangential directions also increases. This is because larger fiber diameters generally indicate a larger amount of cell wall material, which is more prone to dimensional changes due to changes in moisture content.

Lf demonstrates significant negative correlations with TS at -0.642, RS at -0.729, and f_{c0} at -0.645.

Twf shows a significant positive correlation with TS, with a value of 0.662. This significant positive correlation indicates as fiber wall thickness increases, wood tangential shrinkage also tends to increase. This occurs because fiber wall thickness is direc tly related to wood ability to shrink or expand in response to moisture changes [43]. Thicker fiber walls contain more cell material, which can absorb and release water. As wood dries, fibers with thicker walls tend to shrink more, leading to greater tangential shrinkage. Therefore, an increase in fiber wall thickness contributes to a higher degree of tangential movement in wood, explaining the observed positive correlation.

Table 6 presents the Pearson correlation coefficients (r) between the physical and mechanical properties of Cumaru wood.

Table 6: Results of Pearson correlation test ($-1 \leq r \leq 1$) between the physical and the mechanical properties evaluated.

STAT.	f_{c0}	f_{t0}	f_{t90}	f_{v0}	E_{c0}	E_{t0}
$\rho_{ap,12}$	0.001	0.331	–0.304	0.069	–0.015	–0.256
RS	0.684	0.075	0.4	0.104	0.187	0.178
TS	0.603	0.131	0.319	0.221	0.245	0.166

At the 5% significance level, Pearson correlations considered significant by analysis of variance (ANOVA) are underlined.

Table 6 shows a significant positive correlation between RS and f_{c0}, coefficient 0.684. This result suggests that as wood radial shrinkage increases, strength in compression parallel to grain also tends to increase.

A significant positive correlation was also found between TS and f_{c0}, coefficient 0.603. This indicates that an increase in TS is associated with an increase in f_{c0}.

No other correlation was statistically significant at the 5% level, as indicated by non-underlined values. The remaining correlations are relatively weak or negative, suggesting little to no linear relationship between variables analyzed.

Currently, there are no equivalent studies in the literature that allow for a direct comparison of the results obtained in this work. Although some research addresses correlations between anatomical parameters and mechanical properties of wood, the lack of specific investigations on *Dipteryx odorata* highlights a scientific gap that should be explored. This absence of direct references reinforces the originality of the study and underscores the need to expand research in this area, enabling a better understanding of the structural behavior of wood based on its anatomical characteristics.

4. CONCLUSIONS

The conclusions of this study are presented as follows:

1. Significant correlations were identified between anatomical parameters (fiber length, wall thickness, and vessel diameter) and mechanical properties of Cumaru (*Dipteryx odorata*), confirming their predictive potential.
2. Apparent density and selected anatomical traits were shown to be reliable indicators of mechanical performance, particularly for modulus of elasticity and modulus of rupture.
3. Integration of anatomical analysis with traditional mechanical testing offers an innovative, non-destructive approach for wood quality assessment and classification.
4. These findings provide practical contributions to the efficient selection and structural application of Cumaru, reinforcing its role as a sustainable material for civil engineering and construction.
5. This study should be extended to several other tropical species in order to confirm possibility of generalizing the results here obtained.

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