Wood quality of residual branches of Hymenaea courbaril L. from logging in the Amazon rainforest

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4 authors:

Letícia Da Silva Moreira
Universidade Federal de Lavras (UFLA)

José Tarcísio Lima
Universidade Federal de Lavras (UFLA)

Bruno Charles Dias Soares
Universidade Federal de Lavras (UFLA)

Victor Moutinho
Universidade Federal do Oeste do Pará

Original Article

Letícia da Silva Moreira*, José Tarcísio Lima, Bruno Charles Dias Soares and Victor Hugo Pereira Moutinho

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Abstract: Branches remain in the forest environment as logging activity residue. Considering the large size of many Amazonian trees, their branches have considerable dimensions and can contribute to a sustainable wood alternative for various applications. Due to the formation of reaction wood in the branches, relevant macro and ultrastructural changes can occur in its characteristics in relation to the trunk wood. However, the woods of the branches are not technologically well known. Therefore, this work aimed to evaluate the wood quality of branches of *Hymenaea courbaril* L., comparing it with wood of trunks. The extractives and lignin contents, basic density, shrinkage, fiber biometry, microfibril angle and mechanical resistance to compression parallel to the fibers were analyzed. The branch wood had smaller fiber dimensions and a higher microfibril angle than the trunk wood. The basic density was similar between these materials. The linear and volumetric shrinkages were smaller in the branch wood than in the trunk, while the axial shrinkage was higher in the branch. The parallel compressive strength was also lower in the branch wood than in the trunk. The branch wood has properties suitable for products with higher added value such as furniture, decorative objects, floors and utensils in general.

Keywords: forest residues; Jatobá; microfibril angle; reaction wood; wood properties.

***Corresponding author: Letícia da Silva Moreira,** Postgraduate Program in Society, Nature and Development, Federal University of Western Pará, Santarém, Pará, Brazil,
E-mail: moreira.leticia94@gmail.com. https://orcid.org/0000-0003-3985-791X
José Tarcísio Lima and Bruno Charles Dias Soares, Department of Forest Sciences, Federal University of Lavras, Lavras, Minas Gerais, Brazil, E-mail: jtlima@ufla.br (J.T. Lima), bruno.soares_18@hotmail.com (B.C.D. Soares). https://orcid.org/0000-0002-3513-9198 (J.T. Lima). https://orcid.org/0000-0002-6739-3529 (B.C.D. Soares)
Victor Hugo Pereira Moutinho, Forest and Biodiversity Institute, Federal University of Western Pará, Santarém, Pará, Brazil,
E-mail: victor.moutinho@ufopa.edu.br. https://orcid.org/0000-0001-7770-3087

1 Introduction

The Amazon rainforest with its enormous biodiversity plays an essential role for life, including the regulation of the global climate. This importance was recently highlighted in the Climate Change 2021 report (IPCC 2021), which warns of the need to reduce deforestation, and also seek to reconcile environmental conservation and sustainable production. Considering the multiple faces of this sustainability, the social demands in the Amazon region, timber and non-timber resources are important to the regional economy and, in this scenario, it is important to seek alternatives that improve traditional practices and optimize the sustainability of the forest.

According to ITTO (2020), it is necessary to improve the production and use of natural resources so that the decline in the performance of the timber sector, observed in 2020, is overcome when the demand for exports starts to rise again. In this sense, the focus on the use of wood from branches from residues has grown (Lima et al. 2020; Suansa and Al-Mefarrej 2020), due to its potential to increase the availability of raw material and alleviate pressures on forest remnants (Dadzie and Amoah 2015).

The Amazon region has a relevant impact on the supply of tropical wood for the timber industry in Brazil and, due to the large size of the trees, the amount of residual branches from logging is significant. Keller et al. (2004) calculated 156 m^3 ha^{-1} of logging wastes with diameter >10 cm in a forest management area in the eastern Brazilian Amazon, Pará State, Brazil with cutting intensity of 30 m^3 ha^{-1}. This may estimate the production of residues 5 times greater than the volume of trunk wood extracted. Especially for *Hymenaea courbaril*, according to Brasil (2022), the roundwood production was approximately 20,000 m^3 and branch wood generation of 15,000 m^3, between 2017 and 2019, in a sustainable production in Altamira National Forest, under forest concession regime in Pará State. It is estimated that for every 1 m^3 of round wood extracted in forest production in the Amazon, about 0.3 m^3 of wood remains in the forest in the form of branches, with technical and financial feasibility for the production of higher value-added items (Ribeiro et al. 2019).

The environmental regulations regarding forest management in Brazil, specifically in the State of Pará, the Normative Instruction IN-05 published on September 11th, 2015 (SEMAS, 2015), provides for the use of residues generated by logging activity. This normative classifies it as branches, buttresses and remains of trunks and fallen trees from logging, which may also be used as secondary material for the production of wood products and energy (Dionisio et al. 2022). In this sense, the branch logs may be collected and transported along with the trunk logs, which turn viable the branches collecting and hauling, since it would not generate substantial increase in costs and logistics especially for the forest residues (Ribeiro et al. 2019).

Knowledge of the characteristics of wood from the branches can support decisions on the best way to use it, increasing the efficiency of the timber activity by obtaining and valuing by-products (Araújo et al. 2020), while contributing to the strengthening of community forest management, attracting social progress and improving the quality of life of Amazonian communities. The maximum use of the wood produced by the tree is a strategic factor for this approach where the forest must be managed in a reconciled way. However, studies on branches of Amazonian species with timber and commercial potential are still scarce

When considering wood from branches as a potential resource, it is necessary to determine the appropriate strategy to overcome possible limitations, making it suitable for various applications (Suansa and Al-Mefarrej 2020). In this way, Lima et al. (2020) relate that logging wastes from sustainable forest management have the potential to generate electricity for remote regions of the Amazon, as well as to produce charcoal with properties suitable for steel use. On the other hand, wood products may reach highest market values that could increase their income generation. The wood properties are parameters that allows classifying it both for sawn wood and for energy production. In this sense, to optimize the use of waste, these two possibilities can work together to improve sustainability in the management of native forests. Larger diameter branches can be used for lumber production, while thinner branches can be used for bioenergetic purposes.

In branches, reaction wood formation enables to reorient their growth at the tree's crown for optimal exposure of each branch to sun light, as well as to replace a damaged apical shoot by reorientation of an adjacent branch, which becomes the new leader (Aloni 2021). Reaction wood is wood produced by trees in order to orientate stems and branches in response to displacement and the requirements for light (Gardiner et al. 2014). The wood from branches can present changes in its characteristics in relation to the wood from trunks from upright trees, due to the formation of reaction wood. Clair et al. (2006), Ruelle et al. (2011), Dadzie et al. (2018) and Aiso-Sanada et al. (2018) point out differences between anatomical and chemical characteristics of the branch and trunk wood, in addition to those observed in physical and mechanical properties.

The wood popularly known as Jatobá (*Hymenaea* spp.) is one of the most important among Brazilian tropical woods. Along with Ipê (*Handroanthus* spp.), Cumaru (*Dipteryx* spp.) and Maçaranduba (*Manilkara* spp.), it is part of the group of the most traded woods in the Pará state, the main supplier of tropical wood in the country. According to data from SISFLORA (2016), among more than 1000 species, the Jatobá alone represents 5% of the total volume sold in the state, in the period from 2009 to 2015, corresponding to 1,152,297 m^3. Jatobá wood reached one of the highest values in the domestic and foreign market, the second highest after Ipê wood (ITTO 2020). Therefore, increased use of this tree may result in direct economic benefit. Its main end uses include flooring, light and heavy civil construction, furniture, lathed parts and small artifacts (IPT 2013).

The best knowledge about the branches of *Hymenaea* spp. may indicate uses that add value to the residual wood, in addition to revealing possible aptitude of this wood for processing and use similar to trunk wood. This may encourage forestry enterprises, especially those of community management, to maximize the use of their raw material.

The objective of this work was to analyze the wood quality of the branches of *H. courbaril*, comparing it with the wood of the trunk, in order to contribute to a better knowledge and sustainable use of Amazon Forest.

2 Materials and methods

2.1 Origin of the material

The material studied was collected in a Forest Management Unit "Floresta Farm", annual production unit 01 (3°6′15.09″S/55°58′29.24″W), operated by the Rondobel company, located in Nova Olinda I glebe, municipality of Santarém, Pará State, Brazil.

Nova Olinda I glebe has a total area of approximately 86,000 ha. The climate is classified as Amw according to Köppen, characterized as hot and humid, with mean annual temperature between 25 and 28 °C. The rainfall regime is intense with wide variation during the year, with the highest concentration of rain in the period from January to July and the dry season occurs from August to December, with a mean annual rainfall of 1900 mm. The relief is plain, characterized by flat to slightly undulated topography, with predominance of the soil classified as Yellow Latosol in upland areas and Haplic Gleissolo in wetlands (IDEFLOR 2010).

2.2 Collection and sampling procedures

It was selected two trees with diameter at breast height (DBH) of 86 and 96 cm, as well as its branches with diameter at the insertion of the branch into the trunk of 36 and 42 cm, respectively. The trees sampling range was 217 m distance (trees coordinates: 3°6′18.83″S–55°58′24.80″ W and 3°6′17.86″S–55°58′31.80″W). The material was transported to the laboratory, where the anatomical identification of the species was carried out.

Initially, three Jatobá trees were selected, supposed to be *H. courbaril* L. However, the anatomical laboratory evaluations showed that one of them was identified as *Hymenaea parvifolia* Huber, being discarded. Thus, two trees were used in this study. The cost of the tree and the logistical difficulties associated with seasonality prevented the sampling of new trees. To compensate for the reduction in the number of trees, an attempt was made to carry out a more detailed sampling within each tree.

For the anatomical, physical, mechanical, chemical and microfibril angle analyses, three discs were cut from each tree, one removed from the trunk at the DBH and two discs from the branch in the first bifurcation of the tree. A disc was collected 15 cm from the branch insertion point and another disc was positioned 1 m away from the first disc (Figure 1). The positions of the discs were determined in order to avoid the region of basal thickening that occurs at the insertion point of the branches and at the bases of the trunks. A central strip containing the pith was cut from each disc, as shown in Figure 1.

From the central strips of the discs, specimens were cut for all analyses. First, a lateral strip was cut to obtain samples for mechanical testing. Next, the central strip containing the pith was divided into four threads for measuring fiber biometry and microfibril angle (MFA), physical tests and chemical analysis (Figure 2). Due to the sample size, in disc format, it was not possible to cut samples for bending test.

From each central strip, samples were taken at four radial positions. Three positions were sampled in the heartwood: internal (near the pith), intermediate and external. These were positioned at 25%, 50% and 75% distance from the pith, approximately. In addition, a sample of the sapwood was taken. This sampling was carried out in the tension and opposite woods, in each disc from the branches and trunks.

For chemical analysis, samples were taken in three radial positions of both trunk and branch (internal and intermediate in the heartwood and one in the sapwood) of the tension and opposite woods.

2.3 Pith eccentricity

In each branch and trunk disc, the geometric center was marked and the distance between that point and the pith was measured. Then, the pith eccentricity was calculated, according to the IBDF (1984).

2.4 Fiber biometry

Samples for fiber biometry measurement were taken in a stick format in all predefined radial positions in the tension and opposite woods from the branch and trunk. The material was macerated following the methodology used by Franklin (1945). After this step, the material was washed with distilled water to remove the chemical reagents and then dyed with 1% safranin for subsequent slide preparation and measurements using a light microscope.

The Olympus BX-51 microscope with a coupled camera, connected to a microcomputer with the software *Image-Pro Plus* for image analysis, was employed for images acquisition. Twenty fibers were analyzed per sample, with measurements of length, width and diameter of the lumen of the fibers. The cell wall thickness was obtained by the difference between the fiber width and the lumen diameter, divided by two.

2.5 Microfibril angle

For measuring the microfibril angle (MFA), samples with a dimension of 1 cm^3 were produced, which were initially saturated in water. Next, longitudinal cuts, 10 μm thick, were made on the tangential face of the samples in a sliding microtome. The material was macerated according to the method described by Franklin (1945). Then the material was washed and stored in distilled water. After this process, provisional slides were made with distilled water and fiber solution for analysis. To determine the MFA, the polarized light microscopy technique employed by Lima et al. (2004), with the aid of an Olympus BX-51 light microscope, equipped with a polarizing filter and a rotating table with a 0°–360° graduated goniometer. Twenty measurements were carried out per sample.

2.6 Basic density and shrinkage

The basic density was determined according to NBR 11941-02 (ABNT 2003). The maximum shrinkages in the tangential, radial and axial directions were evaluated, in addition to the determination of the volumetric shrinkage, all according to procedures recommended by NBR 7190 (ABNT 1997). The coefficient of anisotropy was determined by the ratio between tangential and radial shrinkages.

2.7 Compression-parallel-to-grain

Compression-parallel-to-grain test was carried out in a universal testing machine, with the test carried out according to the methodology described by BS 373 (BSI 1957), where the values of compressive strength parallel to grain were obtained.

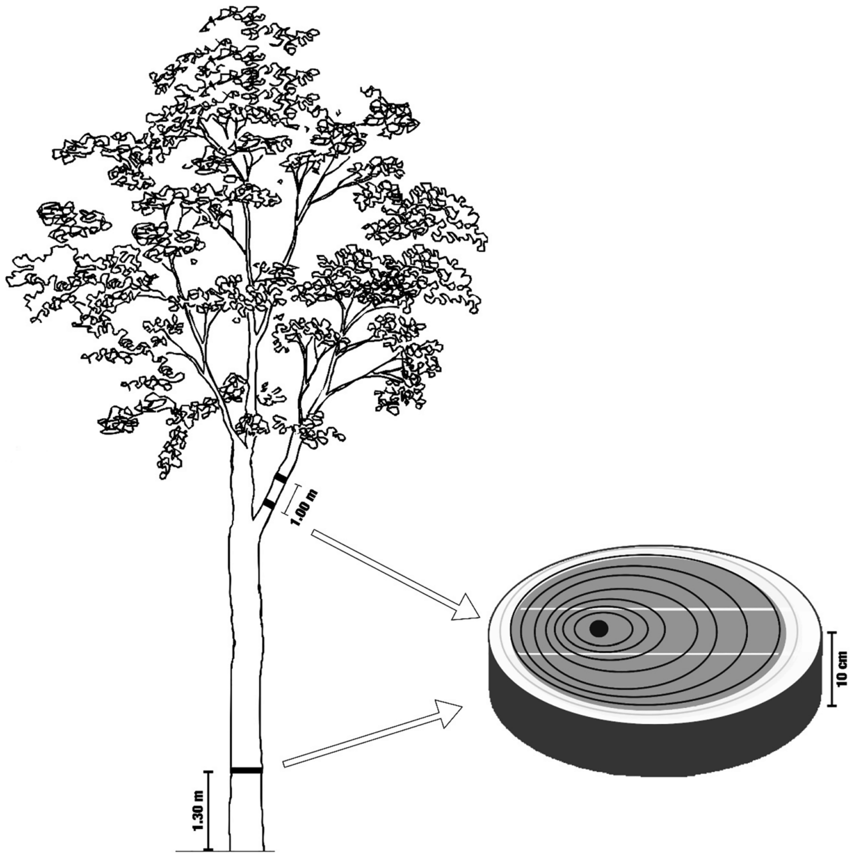

Figure 1: Representation of discs and central strips sampling.

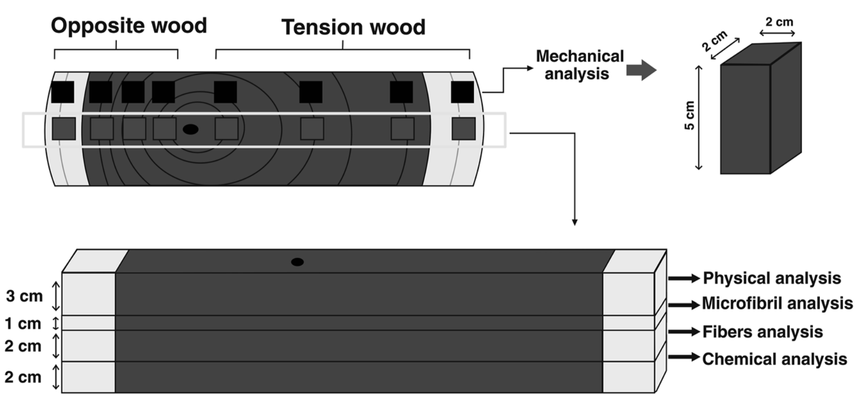

Figure 2: Scheme of sampling the specimens from the strips.

Thirty-two specimens were tested, measuring 20 mm × 20 mm × 60 mm, with the largest dimension in the longitudinal axis, being from the radial positions of the discs, showed in Figure 2, from the tension and opposite woods of the branches and trunks.

2.8 Lignin and extractives content

The air-dried material was milled and classified into 40 and 60 mesh particle sizes. The moisture of the material was determined, followed by extraction of extractives according to the procedures of T 204 (TAPPI T. 2007), with replacement of ethanol/benzene by ethanol/toluene.

The determination of the soluble lignin content was carried out according to the procedure described by Goldschmidt (1971), from the filtrate resulting from the process of determining the insoluble lignin content, which was determined according to the methodology employed by Gomide and Demuner (1986). The total lignin content was obtained through the sum of the soluble and insoluble lignin contents. All samples were analyzed in duplicate.

2.9 Statistical analysis

In addition to descriptive statistics, the results were submitted to the F test of analysis of variance (ANOVA), which had its assumptions analyzed and met, considering a completely randomized design in comparisons between branch and trunk wood and between tension and opposite wood (α = 0.05).

3 Results and discussion

3.1 Pith eccentricity

Despite its intrinsic importance, in this work the eccentricity of the pith is used as an indicator of the occurrence of reaction wood, both in the trunks and in the branches. Thus, the pith eccentricity of the tree 1 branch was 5.22%, while that of the trunk was 5.43%. In tree 2, the pith was 8.20% eccentric on the branch and 8.24% on the trunk. In view of this, although it was not possible to verify whether there was any inclination of the trunk or the ground before the trees were cut, it was possible to classify and compare tension and opposite wood in the trunk discs. According to the eccentricity of the trunk piths, it was possible to assume that tree 2 was more inclined than tree 1.

In the discs of the branches there was eccentricity of the pith similar to that observed in the trunks. Due to its higher leaning in relation to the vertical axis, it was expected that the branch would present higher pith eccentricity than the trunk because of the effect of gravity on the distribution of hormones such as auxins in the wood.

3.2 Microfibril angle

The mean microfibril angles (MFA) and F values found for the branch and trunk woods are shown in Table 1.

Studies on MFA from native Amazonian woods are scarce and information has not been found for MFA of *Hymenaea*, so far. However, it is worth mentioning the fact that the first study on MFA in Amazonian woods was carried out for *Andira parviflora* Ducke and *Sacoglottis guianensis* Benth (Silva 1992).

Table 1: Microfibril angles in tension and opposite woods of branch and trunk of *Hymenaea courbaril*.

Material	Mean (°) (SD)	*p*-Value	Type of wood	Mean (°) (SD)	*p*-Value
Branch	6.50* (2.84)	0.000	Tension	5.96* (2.67)	0.000
			Opposite	7.03 (2.9)	
Trunk	4.425 (1.33)		Tension	4.6* (1.42)	0.0183
			Opposite	4.25 (1.21)	

SD, standard deviation; *, significant at 5% probability of error; ns, not significant.

The mean MFAs of the wood of branch and trunk were statistically different, and the trunk presented lower mean MFA in relation to the branches (Table 1). This result may be related to a possible presence of a higher proportion of juvenile/mature wood in the branches than in the trunk. This hypothesis is better discussed ahead, in a specific section.

A lower mean MFA was found in the tension wood compared to the opposite wood in the branch and trunk (Table 1). Washusen et al. (2005), analyzing wood from *Eucalyptus* branches, found a similar behavior, but with considerably higher magnitude of difference. They report that the higher MFA in the opposite wood in relation to the tension wood in branches is a response to the high compression effort to which the opposite wood is submitted, which can act as a structural complement to the tension wood.

Among the factors associated to microfibril orientation are genetic (Qiu et al. 2008) and hormonal (Bouquin et al. 2003) control acting on microtubule orientation, which in turn is associated with microfibril orientation (Barnett et al. 1998). In addition, rosettes involved in the cellulose synthesis process are also among the factors linked to the orientation of microfibrils. The mentioned synthesis is influenced by growth stresses (Wu et al. 2000). The relationship generally observed is that the higher the tensile stress, the higher the distortion of rosette complexes in the plasma membrane, resulting in lower MFA (Donaldson 2008).

3.3 Fiber biometry

The mean dimensions of the fibers of the branch and trunk, in addition to the results of the F test are shown in Table 2.

According to the F test, the fibers of the *H. courbaril* branches are smaller than those of the trunks (Table 2). This behavior corroborates what was reported by Zhao (2015). All biometric characteristics of the fibers from the trunk were similar between the tension and the opposite wood, except for the diameter of the lumen (Table 2). This result differs from that found by Jourez et al. (2001) for *Populus euramericana*, in which the tension wood had longer fibers and a smaller width than the opposite wood. In fact, Déjardin et al. (2010) report that tension wood is remarkably characterized by the differentiation of longer peculiar fibers, called G fibers, with a thick inner gelatinous layer, which can fill almost the entire fiber lumen. However, most of the fibers from the branches differed between tension and opposite woods.

Table 2: Dimensions of fibers sampled in tension and opposite woods of branch and trunk of *Hymenaea courbaril*.

Material	Mean (SD)	*p*-Value	Type of wood	Mean (SD)	*p*-Value
Length (mm)					
Branch	1.289* (0.21)	0.000	Tension	1.330* (0.21)	0.000
			Opposite	1.249 (0.19)	
Trunk	1.362 (0.22)		Tension	1.358 ns (0.228)	0.743
			Opposite	1.366 (0.215)	
Width (μm)					
Branch	16.85* (2.29)	0.000	Tension	17.40* (2.30)	0.000
			Opposite	16.30 (2.16)	
Trunk	19.28 (2.56)		Tension	19.08 ns (2.56)	0.169
			Opposite	19.47 (2.56)	
Lumen diameter (μm)					
Branch	6.40* (1.96)	0.000	Tension	6.79* (1.98)	0.000
			Opposite	6.02 (1.87)	
Trunk	7.38 (2.15)		Tension	7.14* (2.14)	0.047
			Opposite	7.61 (2.14)	
Wall thickness (μm)					
Branch	5.22* (0.93)	0.000	Tension	5.30* (0.94)	0.024
			Opposite	5.14 (0.92)	
Trunk	5.95 (0.94)		Tension	5.97 ns (0.98)	0.696
			Opposite	5.93 (0.91)	

SD, standard deviation; *, significant at 5% probability of error; ns, not significant.

Aloni (2021) describes the hormonal control in tension wood formation based on wood from trunks, which also can be valid for wood of branches. According to him, for inclined stems of young Populus stems, specific carrier protein PIN3 directs the auxin to the cambial zone in the upper stem side, which activates the cambium and promotes tension wood formation, while in the lower side, PIN3 directs the auxin to the cortex, thus preventing auxin from the cambium of the opposite wood.

Biometric data related to branch fibers were not found in the literature, which did not allow the comparison of results. However, the values measured in the trunk may be compared with those already published for *H. courbaril* (Table 3).

The relationship between fiber length and strength is not very well understood. However, it is known that the cell length is important in determining strength but it is not directly proportional to the length of the cells: rather it has been shown that a minimum length of the cell is necessary in order to ensure sufficient overlap with the cell above and below it in order to transfer stress from one cell to the next (Desch and Dinwoodie 1996). Thus, although the stronger woods are frequently associated with increased cell length, it should be appreciated that it is not the cell length as such is the direct cause of the increase strength; rather the increased length is the consequence of other factors causing increased strength (Desch and Dinwoodie 1996). According to Amidon (1981) fiber length is an important factor in controlling the resistance of paper, mainly under shearing. In *Eucalyptus*, aspects of fiber morphology, such as diameter, affect the processing of wood for paper making (Amidon 1981) for composite products and for preserved timber products (Hudson et al. 1998). Also, the behavior of the fiber diameter is important in explaining variations in density (Malan 1991) and strength properties (Elzaki and Nasroun 1987) due the combined effects of an increase in fiber diameter and a decrease in lumen size. Wall thickness and fiber diameter are the characteristics that often have the most bearing on the density and mechanical properties of wood. Timber strength in general is related to the percentage of fibers present, but this may be much modified by the proportion of cell wall in individual fibers (Chalk 1983). This is not simply a matter of the thickness of the wall, since it is recognised that during the specialisation of the fiber the dominant factor affecting the proportion of cell wall is the elongation of the cell by intrusive growth, which reduces the lumen without affecting wall thickness (Chalk 1983). Density depends on wall material per unit area, but sometimes the influence of wall thickness is outweighed by fiber diameter. The lumen diameter indicates the size of the cavities of the fibers. A direct and obvious inference is that the higher is the lumen diameter, the lower will the wood density be. Also, liquid movement will be favoured by a wider-lumen wood. Most of the discussion relating specifically to the lumen diameter can be inferred from the results in the literature for fiber diameter and fiber wall thickness.

Table 3: Fibers biometry results reported for *Hymenaea courbaril* wood.

Literature	Length (mm)	Width (μm)	Lumen diameter	Wall thickness
Ribeiro et al. (2018)	1.29	20.8	6.87	6.97
Paula (1977)	1.25	17.16	7.54	4.95
Paula (1999)	1.33	19	3.8	4.60

3.4 Lignin and extractives content

Table 4 shows the mean contents of lignin and extractives in the tension and opposite woods of the branch and trunk of *H. courbaril*, in addition to the results of the F test.

The lignin and extractives content found in the branch wood (Table 4) are similar to those reported by Castro et al. (2015) for trunk wood of the same species, and higher than those reported by Carneiro et al. (2009). The branch wood had a higher mean lignin content compared to the trunk, according to the F test. These results are different from that reported by Pettersen (1984) that described contents of lignin of 20% and extractives 13.8% for the same wood species from Honduras. These differences may be related to the type of wood as (tension or normal wood), tree part (branch or stem), different geographic origins, climate and soil conditions that affect wood chemical composition (Pettersen 1984). Santana and Okino (2007), when studying the same species from Amazon, found values in the range of those described in this work for total lignin and extractives contents.

Considering that the trunk needs more strength in compression-parallel-to-grain to support its own weight and the weight of the branches, besides the branches being generally more flexible than the trunk, it was expected that the lignin content in the branch would be lower than in the trunk. According to Donaldson (2019), the orientation and layering of cellulose determines the longitudinal stiffness of the wood while the distribution of lignin determines the compressive strength and pulping properties.

In trunks and branches, statistically similar lignin contents were observed in tension and opposite woods (Table 4). This result differs from what authors such as Pilate et al. (2004) reported, since tension wood tends to have lower lignin content and higher cellulose content in relation to the opposite or normal wood.

Similar to what happened with the lignin content, the extractive content was higher in the branch than in the trunk. However, extractive content was similar between tension and opposite woods for both materials (Table 4). Little is known about the hormonal factors that signal the heartwood formation and deposition of extractives in wood, such as that of *H. courbaril*. Therefore, studies related to physiology need to be developed, seeking to explain the behavior of extractive content in the branch and trunk of this species.

3.5 Basic density and shrinkage

The means for the physical properties of wood of *H. courbaril* from branch and trunk are presented in Table 5. For the basic density of branch and trunk (Table 5), the values were found in agreement with some values reported for *Hymenaea* (Table 6).

Despite being one of the most important anatomical characteristics related to wood density, cell wall thickness, which differs between branch and trunk (Table 2), did not imply a difference in basic density (Table 5). In addition, other anatomical characteristics, such as pore frequency or parenchyma percentage, exert influence on wood density.

The trunk wood shrinkages (Table 5) corroborate Lahr et al. (2016), but were smaller than those described by some studies (Table 6) for *H. courbaril*. For the anisotropic coefficient, some coefficients found in the literature for *Hymenaea* sp. (Table 6) were similar (Evangelista and Costa 2017) or lower (Cavalheiro et al. 2016) than the values found for branch and trunk (Table 5).

According to Table 5, the shrinkages, except axial, were smaller in the branch wood than in the trunk. Higher axial shrinkage is associated with larger microfibrillar angle of the branch fibers (Table 1). The coefficient of anisotropy was also lower in the branch wood, which

Table 4: Lignin and extractives content in tension and opposite woods of branch and trunk of *Hymenaea courbaril*.

Component	Material	Mean (SD)	*p*-Value	Type of wood	Mean (SD)	*p*-Value
Lignin (%)	Branch	31.47* (2.83)	0.000	Tension	30.08 ns (3.58)	0.066 ns
				Opposite	32.49 (1.67)	
	Trunk	27.79 (3.29)		Tension	28.44 ns (3.50)	0.359
				Opposite	27.08 (3.07)	
Extractives (%)	Branch	12.82* (7.34)	0.039	Tension	12.59 ns (6.86)	0.908
				Opposite	13.00 (7.99)	
	Trunk	8.80 (4.39)		Tension	8.24 ns (4.35)	0.555
				Opposite	9.41 (4.59)	

SD, standard deviation; *, significant at 5% probability of error; ns, not significant.

Table 5: Basic density and shrinkage indices in tension and opposite woods of branch and trunk of *Hymenaea courbaril*.

Material	Mean (SD)	*p*-Value	Wood	Mean (SD)	*p*-Value
Basic density (kg m^{-3})					
Branch	861.53 ns (83.53)	0.6221	Tension	864.72 ns (75.31)	0.8303
			Opposite	858.13 (94.08)	
Trunk	848.41 (90.49)		Tension	840.90 ns (91.57)	0.7524
			Opposite	855.91 (95.03)	
Tangential shrinkage (%)					
Branch	5.18* (1.78)	0.0128	Tension	5.52 ns (1.77)	0.2833
			Opposite	4.82 (1.77)	
Trunk	6.87 (1.01)		Tension	7.04 ns (0.97)	0.5130
			Opposite	6.70 (1.07)	
Radial shrinkage (%)					
Branch	3.06 ns (0.88)	0.2033	Tension	3.06 ns (0.99)	0.9933
			Opposite	3.06 (0.77)	
Trunk	3.38 (0.69)		Tension	3.56 ns (0.78)	0.3309
			Opposite	3.21 (0.59)	
Axial shrinkage (%)					
Branch	0.47* (0.34)	0.0057	Tension	0.38 ns (0.25)	0.1271
			Opposite	0.57 (0.40)	
Trunk	0.21 (0.15)		Tension	0.18 ns (0.17)	0.4959
			Opposite	0.24 (0.14)	
Volumetric shrinkage (%)					
Branch	8.50* (2.54)	0.0185	Tension	8.75 ns (2.59)	0.5911
			Opposite	8.24 (2.55)	
Trunk	10.21 (1.58)		Tension	10,51 ns (1.60)	0.4631
			Opposite	9.90 (1.62)	
Coefficient of anisotropy					
Branch	1.70* (0.33)	0.0004	Tension	1.83* (0.31)	0.0257
			Opposite	1.57 (0.32)	
Trunk	2.06 (0.23)		Tension	2.02 ns (0.28)	0.4992
			Opposite	2.11 (0.19)	

SD, standard deviation; *, significant at 5% probability of error; ns, not significant.

results in a better dimensional behavior of this material in relation to the trunk wood and, consequently, it will be less subject to defects, such as cracking and warping, during wood drying (Bergman 2021). However, effects of grain deviation and pith eccentricity, so common in branches, must also be taken into account when testing this material in drying processes.

Except for the coefficient of anisotropy of the branch, the tension and opposite woods were statistically similar in terms of physical properties (Table 5). This fact is not in line with the literature, which in general, describes the tension wood with higher density than the opposite wood. It should be considered that cellulose has a density higher than that of lignin (Kollmann and Côté 1968), making the tension wood, richer in cellulose than the opposite wood, to have a higher density. The similarity in shrinkage between tension and opposite wood may be due to the similarity between the MFA of these woods, whose values were statistically different but close to each other, given that the shrinkages tend to be related with the MFA (Donaldson 2008, 2019). Ruelle et al. (2007), when studying inclined trees of ten tropical species, in five of them they found similar densities between tension and opposite wood.

3.6 Compressive strength parallel to grain

The strength in compression-parallel-to-grain for tension and opposite woods of branch and trunk is shown in Table 7. The values found for trunk wood is close to those found for the genus *Hymenaea* (Dias and Lahr 2004) and for *Hymenaea stilbocarpa* (Lahr et al. 2016).

In trunk wood there was higher strength than in branch wood (Table 7). Although the basic density is similar between these woods, the different mechanical behavior may be associated with the lower MFA found in trunk wood, considering that the lower the MFA, the higher the resistance to this mechanical effort (Barnett and Bonham 2004).

It is noteworthy that, despite the statistically different strength of trunk wood (Tables 5 and 7), branch wood had a higher mean value than some commercial tropical woods. This is the case of Itaúba (*Mezilaurus itauba*) and Garapa (*Apuleia leiocarpa*) woods, with basic density of 910 kg m^{-3} and 920 kg m^{-3} and compressive strength parallel to grain of 69 MPa and 73 MPa, respectively (Dias and Lahr 2004).

Table 6: Basic density, shrinkages and coefficient of anisotropy reported for *Hymenaea*.

Literature (*H. courbaril*)	Basic density (kg m^{-3})	Literature (*Hymenaea* sp.)	Shrinkage (%)			Coefficient of anisotropy
			Tangential	Radial	Volumetric	
Mamonová and Reinprecht (2020)	907	Lahr et al. (2016)	6.72	3.55	–	1.89
Sousa et al. (2019)	848	Cavalheiro et al. (2016)	4.64	3.25	8.3	1.44
Green et al. (1999)	710	Evangelista and Costa (2017)	11.46	6.11	16.94	1.89
Richter e Dallwitz (2000)	820	Simpson and TenWolde (1999)	8.5	4.5	12.7	1.89

Table 7: Compressive strength parallel to grain in tension and opposite woods of branch and trunk of *Hymenaea courbaril*.

Material	Mean (MPa) (SD)	*p*-Value	Type of wood	Mean (MPa) (SD)	*p*-Value
Branch	80.24* (18.20)	0.016	Tension	85.36 ns (17.55)	0.107
			Opposite	74.78 (17.83)	
Trunk	95.81 (23.53)		Tension	96.66 ns (23.40)	0.892
			Opposite	94.97 (25.25)	

SD, standard deviation; *, significant at 5% probability of error; ns, not significant.

The mean compressive strength parallel to the fibers was statistically similar between the tension and opposite woods, both in the branch and in the trunk. Other investigations show that it is common to find this type of result. Ruelle et al. (2007), in a study with ten tropical species, observed a significant difference in compressive strength between tension and opposite wood in only one of them. Soares et al. (2019) studied compressive strength parallel to grain in five *Eucalyptus* species with eccentric pith and observed that in two of these species, tension wood was less resistant to this mechanical stress, compared to the opposite wood.

3.7 Possible influence of juvenile wood on branch wood properties

Several wood properties analyzed in this study showed differences between branch and trunk that drew our attention to a possible higher juvenile wood/mature wood ratio in the branches than in the trunks. In branch wood, microfibril angle and axial shrinkage were higher, while fiber dimensions, tangential and radial shrinkages and strength in compression-parallel-to-grain were lower than in trunk wood.

Ridoutt and Sands (1993) observed a strong correlation between length of fusiform initials of the vascular cambium and fiber length of the secondary xylem, by analyzing these anatomical characteristics in nine different axial positions of *Eucalyptus globulus* 16-year-old. According to these authors, the length of the referred cells decreases from the base to the top, although the rate of decrease is higher for fiber length than for the length of fusiform initials. Furthermore, it is known that the growth of trees such as *H. courbaril* and *E. globulus* is sympodial, i.e., the lateral branches are result of the differentiation of lateral meristems (axillary buds) that initially differentiate for the formation of the structures of primary growth (procambium), which later gives rise to structures that promote secondary growth (vascular cambium).

Considering that the lateral meristem originates a new cambium with juvenile characteristics and smaller initial fusiform, years after the establishment of the tree and maturation of the cambium at the base, it is understood that the base of the trunk would produce mature wood for a longer time than the base of the branches. Thus, the average properties of the wood at the base of the branch tend to have more marked juvenile wood characteristics, unlike the wood at the base of the tree, which tends to present average properties of mature wood.

4 Conclusions

Although it develops under a more inclined condition, the wood of the branch did not present higher eccentricity of the pith compared to the wood of the trunk of *H. courbaril*. The tension wood of this species showed changes in only some biometric characteristics of the fibers and in the microfibril angle in relation to the opposite wood in the branch and trunk. As for the chemical, physical and mechanical strength properties evaluated, the tension wood presented a behavior similar to that analyzed for the opposite wood, both in the branch and in the trunk.

The branch wood had smaller fiber dimensions and higher microfibril angle than the trunk wood. The basic density is similar between these materials; however, the tangential, radial and volumetric shrinkages were lower in the branch than in the trunk, while the axial shrinkage was higher in the branch. The compressive strength parallel to grain was also lower in the branch than in the trunk of *H. courbaril*. These findings are probably related to the presence of juvenile wood in a higher proportion in the branch than in the trunk.

According to the results observed, the wood from the branch of *H. courbaril* has properties suitable for use by the sawn wood industry, in the manufacture of products with increased added value, such as decorative objects, furniture, various artifacts and utensils in general. Another potential use for wood from branches with higher added value is for the production of floors, especially those made with smaller pieces.

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