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Wood from Forest Residues: Technological Properties and Potential Uses of Branches of Three Species from Brazilian Amazon

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Abstract: Branch wood presents potential volumetry that may have several applications, and its use may improve forest management efficiency in the Amazon. However, there is a lack of knowledge regarding the properties of branch wood when compared to the stem or what its potential applications might be, considering the possible variability of wood formation in branches. This study aimed to characterize physically and mechanically the branch wood of *Dipteryx odorata*, *Hymenolobium petraeum* and *Hymenaea courbaril* and to compare them with their respective stems. No significant statistical differences were observed for the basic density between the branch and stem woods. The branch wood of *Dipteryx odorata* and *Hymenaea courbaril* showed a lower coefficient of anisotropy (1.23 and 1.99, respectively) than the stem wood (1.62 and 2.49, respectively). *D. odorata* showed similar mechanical properties between the branch and stem, except for hardness, while *H. petraeum* and *H. courbaril* branch wood showed lower strengths when compared to the stem wood for all mechanical tests, except for the shear strength test. Branch wood has similar potential uses to stem wood and can be used for non-structural purposes such as small artifacts, decorative items, furniture, tools and panels composed of short, glued pieces.

Keywords: Amazon rainforest; *Hymenaea courbaril*; *Dipteryx odorata*; *Hymenolobium petraeum*; logging wastes; tropical timber; sustainable forestry

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1. Introduction

There is a growing trend in using forest residues as forest management and conservation methods in tropical forests [1,2]. Studies suggest that the use of branches associated with stems maximizes forest productivity, increasing the value of forest areas [3]. It is estimated that for each 1 m^3 of log harvested in management units in the Brazilian Amazon Forest, approximately 0.3 m^3 of waste in the form of branches is produced [4,5].

Between 2009 and 2015, in the low Amazon region in Pará state (Brazil) alone, approximately three million cubic meters of logs were produced [6]. Considering the above estimate, that means that approximately 900,000 m^3 of branch wood was potentially available for use in the region. However, the use of sawn wood from branches as a secondary product is still challenging due to the possible non-uniformity of its properties due to the reaction wood formation or variable dimensions [1,2,7].

Branch wood has a different formation when compared to the usual wood from straight tree stems [8,9]. Due to the gravitropic forces, tension wood is formed on the upper side of the leaning branches [10]. Changes in the chemical and anatomical constitution of the tension wood xylemic tissue [2,11] can also cause changes in the properties of the wood, such as higher density [12,13], higher longitudinal shrinkage [14], lower compressive strength [15] and higher tensile strength than normal wood [16].

Previous studies found differences between stem and branch wood both in terms of chemical and anatomical characteristics [9,17,18] and in technological properties [19–22]. However, there is a lack of studies on tropical Amazon wood species with commercial potential, especially from the Brazilian Amazon, Brazil's main tropical wood producer and one of the world's largest suppliers of tropical wood [23]. The research about the technological behavior of the branches wood can support the improvement of the forest harvesting efficiency in the Amazon.

Thus, considering the fundamental characteristic of the wood as an anisotropic and heterogeneous material [16], knowledge of wood's physical and mechanical properties is essential for defining its use [24,25], especially the group of the most traded wood species and the relevant volume of residues generated by its harvesting, as reported by Cruz Filho and Silva (2009) [26] and Numazawa et al. (2017) [27]. The study of branch wood properties and possibilities for its use supports the referral of this alternative wood resource [28]. In addition, it is important to highlight that removing large branches would have a low impact on the nutrient cycling in the forest. Because of their big dimensions and high wood durability, these branches remain above the ground for a long time. The main contribution to litter formation, on the other hand, is the leaves, followed by thin branches [29].

The objective of this research was to evaluate whether the branch wood of three commercials relevant Amazon wood species has similar physical and mechanical characteristics to the stem and to propose the use of the material.

2. Material and Methods

2.1. Material

Branches from three species of the Fabaceae family were chosen: (i) *Hymenolobium petraeum* (Angelim-pedra), (ii) *Dipteryx odorata* (Cumaru) and (iii) *Hymenaea courbaril* (Jatobá). The samples were collected in a sustainable forest management area in the Mamuru—Arapiuns plot, Santarém—PA, Brazil (3° 00′ 20″ S 56° 01′ 1967″ W).

The species were selected based on a list of species with the highest traded wood volume between 2009 and 2015 [6]. During the collection, samples were identified vernacularly by the Rondobel company, which supported the project and donated the material for analysis. The species were scientifically identified by specialists from the Federal University of Western Pará (UFOPA, Santarém, Brazil).

Four trees per species were selected at random within the study area. The first branch after the first bifurcation of each tree with a diameter above 40 cm was collected. The branch logs were cut and split into radial pieces (10 × 10 × 200 cm). The samples contained only heartwood (visual distinction), with greater dimension in the longitudinal direction. Wood from the trunk of one tree was also collected as a reference value for the branch properties. A central plank was taken from a log at 1.3 m above the ground, under the same conditions and dimensions as the branch material.

2.2. Physical Properties

A minimum of 24 specimens from the branches and 12 from the trunk with dimensions of 25 mm × 25 mm × 100 mm were tested for each species, as dictated in D 143 [30] standard protocols.

The basic density (ρ_{bas}) was calculated by the ratio between the oven-dried mass (103 ± 2 °C) and saturated volume (rehydration in deionized water to constant volume) of the stem and branch. The apparent density at 12% moisture content ($\rho_{12\%}$) was determined as the ratio between mass and volume in the same condition after the saturated samples reached a moisture content equilibrium in an air-conditioned room (21 ± 3 °C; 65% H).

The samples were also measured in the saturated condition and then oven-dried for calculation of the linear and volumetric contractions and the coefficient of anisotropy (CA), which is the ratio between tangential and radial contraction. The D 143 [27] standard methods were applied to determine the physical properties.

2.3. Mechanical Properties

Compressive strength parallel to fibers (25 mm × 25 mm × 100 mm), strength and stiffness in static bending (25 mm × 25 mm × 410 mm), shear strength (50 mm × 50 mm × 63 mm) and Janka hardness (50 mm × 50 mm × 150 mm) were determined according to standard D 143 [30], with an electro-servo-mechanical universal testing machine (EMIC, model DL 30,000, Curitiba, Brazil).

For shear strength and compressive strength parallel to the fibers in branches, a minimum of 25 samples per species were tested, while for static bending and Janka hardness, a minimum of 20 and 15 samples were tested, respectively. The exception was *Hymenolobium petraeum*; part of the material was misplaced during the transportation between the fieldwork and the laboratory, resulting in 15 and 8 samples for static bending and Janka hardness, respectively. From the stem, a minimum of 10 samples per species were tested in each analysis.

The characteristic value in the parallel compression of the branch wood and the strength classes were determined by Equation (1), as proposed by the NBR 7190 standard [31].

$$f_{c0k} = \left(2\,\frac{f_1 + f_2 + \ldots + f_{\frac{n}{2}-1}}{\frac{n}{2} - 1} - f_{\frac{n}{2}}\right) \quad (1)$$

where
f_{c0k} is the characteristic value of resistance to parallel compression;
f_n is the value of resistance to parallel compression in the nth position with the values ordered in an increasing way;
n is the total number of samples.

2.4. Data Analysis

The study was carried out with two treatments (stem and branch) and 8–10 repetitions. The data were submitted to the t-test (α = 0.05) for data with normal distribution and the Wilcoxon test (α = 0.05) for data with non-normal distribution.

3. Results

3.1. Physical Properties

No significant differences were observed in basic density and apparent density when comparing branch and stem wood for the species *Dipteryx odorata* and *Hymenaea courbaril*. However, it was observed that for the species *Hymenolobium petraeum*, both basic and apparent density were lower in the branch (Table 1).

Table 1. Branch and stem wood basic and apparent density of the evaluated species.

Species		Variable ($g.cm^{-3}$)	Branch	Stem	T Value
Hymenaea courbaril	Mean (min.–max.) CV	$\rho_{12\%}$	0.929 (0.822–1.005) 5.41%	0.949 ns (0.887–1.042) 4.69%	0.1455
		ρ_{bas}	0.805 (0.715–0.872) 5.54%	0.826 ns (0.775–0.903) 4.22%	0.06859
Dipteryx odorata	Mean (min.–max.) CV	$\rho_{12\%}$	1.098 (0.991–1.221) 6.21%	1.100 ns (1.034–1.198) 4.91%	0.8816
		ρ_{bas}	0.941 (0.843–1.059) 7.27%	0.964 ns (0.907–1.032) 4.21%	0.3563

Table 1. *Cont*.

Species		Variable ($g.cm^{-3}$)	Branch	Stem	T Value
Hymenolobium petraeum	Mean (min.–max.) CV	$\rho_{12\%}$	0.712 (0.567–0.894) 14.16%	0.777 * (0.706–0.816) 5.45%	0.03516
		ρ_{bas}	0.596 (0.483–0.739) 13.67%	0.648 * (0.588–0.682) 5.52%	0.03917

$\rho_{12\%}$: density at 12% moisture content; ρ_{bas}: basic density; CV: Coefficient of variation; *: statistically significant difference; ns: non-significant difference on the same line for each property.

H. courbaril and *D. odorata* branch wood presented greater radial contraction ($p < 0.05$) when compared to the stem wood (Table 2). As for the branch tangential and volumetric contraction, these values were lower only for *H. petraeum*. The branch wood volumetric contraction was lower for *D. odorata* and *H. petraeum*. The observed CA was also lower in the branch wood for *H. courbaril* and *D. odorata*.

Table 2. Total shrinkage and coefficient of anisotropy for *Hymenaea courbaril*, *Dipteryx odorata* and *Hymenolobium petraeum*.

	Shrinkage (%)								CA	
	Tangential		Radial		Axial		Volumetric			
Species	**B**	**S**	**B**	**S**	**B**	**S**	**B**	**S**	**B**	**S**
Hymenaea courbaril	4.37	4.96 ns	2.26	2.02 *	0.25	0.21 ns	6.58	8.36 ns	1.99	2.49 *
Dipteryx odorata	5.90	5.59 ns	4.98	3.58 *	0.20	0.17 ns	10.80	9.12 ns	1.23	1.62 *
Hymenolobium petraeum	5.18	7.04 *	3.55	4.57 *	0.22	0.17 ns	8.70	11.44 *	1.49	1.54 ns

CA: coefficient of anisotropy; B: branch; S: stem; *: statistically significant difference; ns: non-significant difference between branch and stem for the same property and species.

3.2. Mechanical Properties

There were no significant differences between *D. odorata* branch and stem wood for mechanical characteristics, except for the hardness test. *H. courbaril* and *H. petraeum* branch wood showed statistically lower values than the stem wood in all evaluated mechanical tests, except shear strength (Tables 3 and 4).

Table 3. Resistance to parallel compression (f_{c0}), shear strength (f_{v0}), modulus of rupture in static bending (f_M) and modulus of elasticity in static bending (E_{M0}) of *Hymenaea courbaril*, *Dipteryx odorata* and *Hymenolobium petraeum*.

Species		f_{c0} (MPa)		f_{v0} (MPa)		f_M (MPa)		E_{M0} (GPa)	
		B	**S**	**B**	**S**	**B**	**S**	**B**	**S**
Hymenaea courbaril	Mean CV	85.02 14%	94.25 * 16%	19.23 17%	18.23 ns 18%	107.73 24%	157.72 * 21%	11.43 28%	18.82 * 20%
Dipteryx odorata	Mean CV	89.21 13%	91.04 ns 8%	17.87 14%	16.68 ns 10%	150.86 22%	165.74 ns 13%	19.27 15%	19.19 ns 8%
Hymenolobium petraeum	Mean CV	48.30 18%	65.05 * 12%	14.65 29%	13.49 ns 18%	63.88 43%	90.34 * 9%	7.35 51%	13.83 * 11%

B: branch; S: stem; CV: coefficient of variation; *: statistically significant difference; ns: non-significant difference between branch and stem for the same property and species.

Table 4. Mean values for the Janka hardness test on the transverse (f_{Hc}), tangential (f_{Ht}) and radial (f_{Hr}) face.

Species		f_{Hc} (kN)		f_{Ht} (kN)		f_{Hr} (kN)	
		B	S	B	S	B	S
Hymenaea courbaril	Mean CV	14 12%	16.70 * 17%	11.20 17%	16.40 * 18%	12.40 13%	16.60 * 21%
Dipteryx odorata	Mean CV	13.21 12%	12.06 * 6%	12.96 15%	14.14 * 3%	13.05 17%	12.84 * 14%
Hymenolobium petraeum	Mean CV	8.45 16%	7.84 ns 3%	6.20 36%	5.55 ns 9%	6.39 35%	6.38 ns 7%

B: branch; S: stem; CV: coefficient of variation; *: statistically significant difference; ns: non-significant difference between branch and stem for the same face and species.

Table 5 shows the characteristic value of the compressive strength parallel to the wood fibers from the branches of the three species, classified in the strength classes according to the NBR 7190 classification [31].

Table 5. Characteristic value of compressive strength parallel to branch wood fibers.

Species	Source	f_{c0k} (MPa)	Class
Hymenaea courbaril	Branch	71.849	C60
Dipteryx odorata	Branch	79.328	C60
Hymenolobium petraeum	Branch	38.948	C30

4. Discussion

4.1. Physical Properties

It was observed that the basic and apparent density of *H. courbaril* and *D. odorata* branch wood did not differ from the stem wood values. They were also similar to the values observed in other research for stem wood of the same species [32–38]. For *H. petraeum*, these values are lower than the stem wood values, although it should be noted that they corroborate the results from the literature for stem wood of the same species [39,40].

The results indicate that the branch wood has somehow similar use to the stem wood, such as small decorative items, tools, furniture or flooring. Density is one of the main parameters for assessing quality and indicative of wood use. It is the product of different wood anatomical characteristics, and it has a direct and indirect relationship with several other wood characteristics [41], such as mechanical properties [42–45], best energetic product [46–49] and material durability, machinability and workability [50,51].

The similarity in density values for *H. courbaril* and *D. odorata* may be due to the branch density being an average of the tension wood and the opposite wood [52]. Thus, given the lower proportion of tension wood, the density of this type of wood does not have a significant influence on the mean value of wood density [14].

For *H. petraum*, the significant difference may be related to the heterogeneous occurrence of resin oil apparent exudation, more present in stem wood, which contributes to high variation in density when compared to branch wood.

Regarding the branch wood dimensional stability, differences were observed depending on the species. The radial contraction of *H. courbaril* and *D. odorata* branch wood was significantly greater than the stem wood. The presence of a gelatinous layer inside the tension wood fiber influences changes in dimensional stability in relation to normal wood [14].

However, the branch wood values for tangential contraction of these two species did not differ from the stem wood. The isolated evaluation of these two factors is not sufficient to qualify the dimensional stability of wood [16,53]. Thus, the ratio between tangential and radial contraction or coefficient of anisotropy is a more appropriate index, as it allows us to determine the dimensional behavior of a part [54]. The farther it is, the greater the dimensional instability, increasing the tendency to defects when drying and decreasing its quality for uses such as flooring and window frames [55].

In comparison to normal wood, the modification of density and dimensional stability in tension wood does not occur as evidently as in compression wood [14]; in general, it is assumed that tension wood has a higher density than normal wood [56–58]. However, this property is highly variable in angiosperm tension wood, in which more complex factors affect density depending on the anatomical configuration [49], thus being differentiated between species [59,60].

Tension wood has an excessive axial contraction due to the presence of a gelatinous layer or a growth stress release during water flow and contraction of the wood [14]. However, due to the low microfibril angle of the tension wood, this leads to infer insignificant longitudinal contraction and, in this case, according to Boyd [61], the high microfibril angle of the S1 layer influences this excessive longitudinal contraction since the S2 layer, from a smaller angle, may have less thickness in that wood. This dimensional behavior was not verified for the branch wood since the longitudinal contraction remained insignificant.

The branch wood coefficients of anisotropy for *H. courbaril* and *D. odorata* were lower than the stem wood and showed no differences in *H. petraeum*. According to the classification proposed by Durlo and Machiori [62], *H. petraeum* and *D. odorata* branch wood can be classified as dimensionally excellent (CA $\leq$ 1.5), while *H. courbaril* has normal dimensional stability (1.5 > CA $\leq$ 2.0).

As noted, *H. petraeum* wood showed lower values for basic and apparent density and lowered tangential and volumetric contraction. Volumetric contraction is the product of other linear contractions, more influenced by tangential contraction [63–65]. As tangential contraction values for *H. petraeum* were lower, this influenced the wood's lower total contraction. In addition, less dense woods, in general, have lower wall thickness and, consequently, less contraction during water outlet [66]. Nakano [67] observed that the wall thickness is related directly to the physical properties of the wood. Andrade et al. [47] also stated that the lower cell wall thickness associated with the lower density of the wood decreases the wood hygroscopicity due to the decrease in free microfibrils and hydroxyls per area, decreasing the volumetric material changes.

Both *H. courbaril* and *D. odorata* branch wood have high dimensional stability (lower CA), which makes them desirable for uses such as window frames or higher value-added products, such as high-end furniture or flooring. *H. petraeum* wood, although less dense, presented similar contraction values to the stem, including less tangential and volumetric contraction, and can be sold for the same uses, such as light civil construction, furniture and decoration [39].

4.2. Mechanical Properties

The results of the mechanical properties observed for the branch are similar to those observed by other authors for stem wood from the same species in this study [68–71].

During the wood parallel compression and static bending tests for *H. courbaril* and *H. petraeum*, some samples apparently free from defects broke catastrophically, resulting in values considerably below the average, which resulted in high coefficients of variation. As previously mentioned, the branch wood presents tension wood, which has a different mechanical behavior due to changes in its composition. In the case of compressive strength parallel to the fibers, the lower lignin content in this type of wood may result in lower resistance due to changes in the wood microstructure [72–74], associated with the significant influence of the microfibril angle on the wood mechanical behavior [75].

Based on the observed results, the use of *H. courbaril* and *H. petraeum* wood for structural purposes in solid form is not recommended since visually healthy portions of wood may have low load capacity. It should be noted that a minority of samples had such defects, but as this work aimed to use them commercially, these values cannot be considered outliers. Its exclusion from the data set could imply risks not only to the structure but mainly to users.

In all tests, except for shear strength, *H. courbaril* branch wood presented statistically lower values than stem wood. This behavior was also observed for *H. petraeum* wood, except for Janka hardness and shear strength. Unlike the other two species, no statistical differences were observed for *D. odorata* branch wood when compared to stem wood, except for the Janka hardness test.

Janka hardness test values for branch wood are similar to those described in the literature for stem wood in the same species studied here [38,40,76]. The wood hardness can be used as an important parameter in the indication of wood for floors and decks [77], and this property is highly influenced by wood density [72].

H. courbaril and *D. odorata* branch and stem wood presented high values in the Janka hardness test both in the normal and parallel direction to the fibers, considered as high hardness wood, according to the LPF classification [78], which indicates suitability for use in the production of floors in general. New studies that evaluate characteristics such as abrasion, roughness and resistance to impacts are important in this sense.

The characteristic values in parallel compression classify *H. courbaril* and *D. odorata* wood as C60, the largest class in NBR 7190 [31], and *H. petraeum* as C30, the second smaller (Table 5).

The resistance classes aim to eliminate the need for a complete wood mechanical characterization before its structural application. With the resistance to parallel compression (fc0k) calculation value, a sawn wood lot is classified in a resistance class, and the values of the other mechanical properties are obtained according to each class. This classification still depends on a visual assessment of the pieces, where pieces with defects, such as knots, grain deviations, etc., are not in a resistance class.

ASTM D143 secondary method [30] was adopted because it proposes reduced dimensions samples, which is important for obtaining parts free from defects since the branches presented grain deviation. The studied branch wood has properties suitable for structural use when free from defects. However, the presence of these defects, such as the reported grain deviations or invisible internal defects, must be considered, as these can drastically reduce the wood's mechanical properties. As the resistance classes classification occurs through parallel compression, and the properties in bending are more severely affected by grain deviation, defects can be an even greater problem depending on the wood destination.

In contrast to *H. courbaril* and *H. petraeum*, *D. odorata* branch wood presented a great mechanical similarity to stem wood. This result indicates that this branch wood can be used in an equivalent way. In general, *D. odorata* wood can be used for heavy civil construction or decorative purposes and for window frames and domestic floor production [39], which points out the high value that can be added to branch wood that remains in the post-harvest forest.

Before *H. courbaril* and *H. petraeum* branch wood is used for structural purposes, the reason for the sudden ruptures observed in the static bending test must be understood. The branches have three types of wood with different characteristics: reaction wood, opposite wood and lateral wood. If the rupture is linked to any of these three types of specific wood, it is still possible to apply this material for other uses other than structural.

H. courbaril and *D. odorata* branch wood presented higher density. Based on this and their other properties, which are similar to the stem wood, and considering the difficulty of obtaining large wood pieces with no grain deviation, they can be applied to other uses that require smaller pieces, such as small artifacts, decorative pieces, furniture, tools, panels composed of short, glued pieces and various utensils that would not be influenced by inclined grain.

Another application is for parquet flooring production. As this type of floor consists of small solid pieces, the problem of grain deviation found in branch wood is avoided, but additional tests to determine the wood lifespan and viability on floors are also recommended.

Branches generally show more tortuosity than the main trunk, which can have a logistic or financial impact on their transportation out of the forest. However, Ribeiro et al. [4] confirmed the viability of harvesting and processing these large branches from many Amazon timber species, supporting the need for a better evaluation of this timber source.

5. Conclusions

Dipteryx odorata, *Hymenaea courbaril* and *Hymenolobium petraeum* branch wood have similar physical characteristics to stem wood and may have the same commercial applications.

Only *Dipteryx odorata* branch wood presented mechanical performance similar to stem wood. However, due to the grain deviation present on branches, it is not recommended to use solid branch wood for structural purposes.

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