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Potential of three woody species from the Brazilian Cerrado for pulp and paper production

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Abstract
The usage of vegetal fibers coming from the wood of planted forests as a source of cellulose for paper production, has placed Brazil in a prominent position in the worldwide economic scenario, being that one of the best alternatives of value aggregation to this natural material. This research has evaluated the potential of three woody species of occurrence in the Cerrado, a Brazilian Biome, as a source of alternative raw material to alien species, nowadays widely used in Brazil for the pulp and paper industry. Wood radial samples of Cedrela fissilis, Cecropia sp. and Genipa americana with 12 years of age were collected in a peri-urban are of the city of Goiânia, through the non-destructive method, for the study on fiber's morphology and basic density. With the data obtained it was possible to determine the felting index, coefficient of flexibility, wall fraction and Runkel index, for fibers qualitative evaluation. The careful evaluation of the results – and the detailed comparison with other species – made it possible to affirm that only the wood of Cedrela fissilis and Cecropia sp. had had potential for the proposed objective. Therefore, relevant aspects for the complementation of this research are pointed.

Keywords
Wood quality — Fiber morphology — *Cedrela fissilis* — *Cecropia sp.* — *Genipa americana.*

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1. Introduction

For being renewable, recyclable and biodegradable natural sources, vegetable fibers have been associated with the expansion of possibilities for exploiting natural resources with aggregated value (Cunha et al. 2022). As an example, we can mention its use in the production of cellulosic composites, such as paper, representing an alternative of great technological importance (da Silva et al. 2022).

Brazil is a world leader in the cellulosic pulp sector, using vegetable fibers from commercial forests as raw material, mostly extracted from exotic species - and hybrids - of the genus *Pinus* and *Eucalyptus* (IBÁ 2022). Nowadays, the country has about 9.93 million hectares of commercial forests, with 35% of the planted areas being used by industries in the pulp and paper segment (IBÁ 2021), demonstrating its economic and social relevance.

In this universe, vegetal fibers of native species have been evaluated as an alternative source of raw material to alien species, specially to *Eucalyptus*, in the production of pulp and its derivatives. As an example: fibers of the manioc stem (*Manihot* sp.) (Azzini et al. 1996a), fibers of the sugar cane straw (*Saccharum* sp.) (Azzini et al. 1996b), Açaí's fibers (*Euterpe oleracea* Mart.) (de Melo et al. 1974), bamboo's fibers (*Bambusa vulgaris* Scharad. ex J. C. Wendl.) (Borges et al. 2018), "tucum's" fibers (*Bactris inundata* Mart.) (P reira et al. 2002liim), the vegetal fiber of "buriti" (*Mauritia vinifera* Mart.) (Cattani, 2016; da Silva et al. 2022) and coconut fibers (Cardoso & Gonçalves 2016).

The evaluation of specie's potential for pulp and paper, starts with the study of the anatomical structure, particularly under the light of the fiber's morphology.

The fibers are part of the anatomical constitution of the wood, having as its main function the vegetal mechanic support (Lima et al. 2021) and because it is an anisotropic material, the wood and its cellular components can present variations in their properties in relation to the direction in which it is being worked on (Trevisan et al. 2017). Thereby, the morphological characteristics can vary between species, between trees and within the same tree, through growth rates and tree age, and are controlled both genetically and phenotypically, by envi-

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ronmental, geographic, and topographic influences (de Miranda & Castelo 2012).

Another important parameter is the fundamental chemical constitution of the wood (Chambi-Legoas et al. 2021), 2018), which together with the anatomical characteristics, defines the wood basic density. According to the same author, the wood basic density is one of the most used index to evaluate wood's quality, because it is easily determined, varies between species and individuals of the same species, between location and inside of the same population, due to genetic and environmental factors (Zobel 1965).

For the industry of pulp and its derivatives, an adequate evaluation of the wood basic density precisely provides indications about the impregnation of wood chips and process yield, and generally is associated with the characteristics of quality and physical-mechanical resistance of the cellulosic pulp (Talgatti et al. 2020).

Even though it is generally studied as a solo characteristic, the wood basic density is considered as a dependent component of the proportions, size and number of fibers and of these cells wall thickness, among others (Coelho 2021).

In this research, we evaluated the potential of three species of widely occurrence in the Cerrado biome for the production of pulp and paper, aiming to contribute with filling the gap of information regarding the aptitude of native species for this purpose. As a starting point, the morphological study of the fibers and the basic density of the wood were chosen as parameters.

2. Material and Methods

This research was conducted in a forestry recovery area popularly known as "Cinturão Verde", located under the coordinates 16°36'00.50''S and 49°16'45.96''W, with an average altitude of 740 meters above sea level, in the city of Goiânia – GO. In 2004, there were planted in the area a great diversity of native species of the Cerrado biome. The climate in the region is classified as Aw (tropical with dry season in winter) (Cardoso et al. 2014), with annual average temperature of 22.5 °C and average rainfall of 1.460 mm; the original vegetation is classified as semideciduous state forest, with predominance of a dystrophic red latosol (Morales et al. 2012).

It was selected six trees of the species *Cedrela fissilis* Vell. (Meliaceae), *Cecropia* sp. (Urticaceae) and *Genipa americana* L. (Rubiaceae) with 12 years old and commonly known as "Cedro", "Embaúba" and "Genipapo", respectively. The wood samples were obtained from 1.30 m above ground, by using a non-destructive method with the aid of an increment probe (**Figure 1**), and a caliper for measuring the diameter at breast height (DBH). The average values for the DHB were respectively of 28.4 cm (18.9 – 36.9), 22.4 cm (14.8 – 25.9) and 22.6 cm (17.9 – 27.4).

The wood's basic density of the species was determined by using the method of maximum moisture content, in accordance to what was recommended by the NBR 1194:2003. The basic density calculation was made in conformity to the equation 1. In which we obtained the values per tree and per specie.

$$Bd=\frac{1}{\left(\frac{m_1}{m_2}\right)-0{,}346} \quad (1)$$

In which: Bd = basic density (g.cm^{-3}); m_1 = wet sample weight in grams; m_2 = dry weight in oven at 105± 2 °C, in grams.

For each species, the relationship between wood basic density and DHB was determined, since diametral growth can influence wood properties, including density (Sette Jr et al. 2016).

For the morphological study of the fibers, the material was prepared as recommended by Franklin (1945). Small wood fragments were taken from radial subsamples (in the positions 0, 50 and 100% of the ray) of each tree, as illustrated in Figure 1, and put in test-tubes with a macerating solution of acetic acid and hydrogen peroxide, in the proportion of 1:1. Posteriorly, the test-tubes were placed in an oven at 60 °C for period of 24 hours, or until the samples were whitish.

From the fiber's solution suspension, a small portion were stained in alcoholic safranin and used in the preparation of temporary histological slides, which were utilized to obtain digital images under light microscopy. The following parameters were measured: fiber total length (40x magnification), wall thickness, lume diameter and fiber width (400x magnification). For each of these parameters, it was made 30 measurements per individual (Wheeler et al. 1989). The images were analyzed in the software Image Pro Plus (version 5.0) and the results of the measurements were used for the calculation of the fiber wall fraction, felting index, coefficient of flexibility and Runkel index (Foelkel & Barrichelo 1975), as presented in **Table 1**. These parameters are an indicative for the cellulosic pulp and paper's quality.

A variance analysis (ANOVA) was applied aiming to verify the effect of the different genetic materials on each studied property, the average values were compared by the Tukey test adjusted to 95% of probability.

3. Results and Discussion

Higher values of basic density were found for *G. americana* (0.58 g.cm^{-3}), while the lowest were seen to *Cecropia* sp. (0.30 g.cm^{-3}), with variation up to 93% between

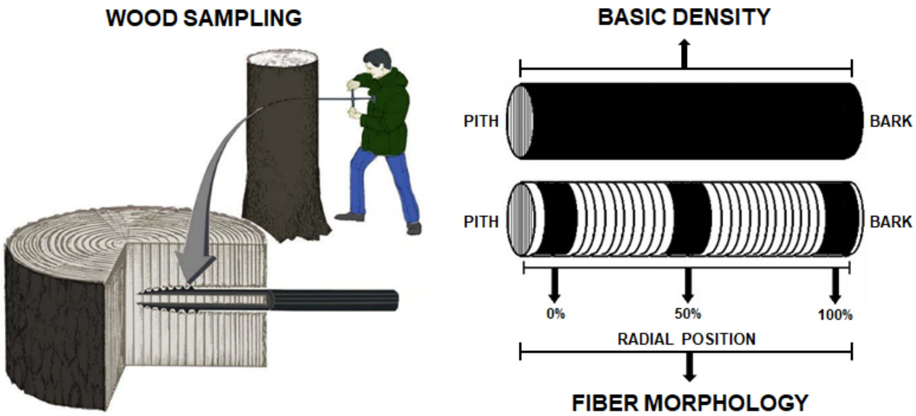

Figure 1. Obtainment of the species' wood samples, through the non-destructive method, for the determination of the basic density and the study of fiber morphology. Adapted from Jozsa (1988).

Table 1. Denomination and relationship between equations for the valuation of the potential of the species for the production of pulp and paper. Fiber average length (L), fiber width (W), Wall thickness (T) and Lume diameter (D)

Denomination Relationship	Relationship
Felting index	L/W
Coefficient of flexibility	(L/W) x 100
Wall thickness	(2T/W) x 100
Runkel index	2T/D

species. *C. fissilis* presents a value of basic density intermediary (0.42 g.cm^{-3}) (Table 2).

Figure 2 shows that has not been observed a relationship between the wood basic density and the diametrical growth of the trees.

In Table 3 we observed a heterogeneity in the dimensions of the fibers, such as the length of the *G. americana* showed the highest values (1387.04 μm) while the lower width (24.59 μm); *C. fissilis* the lower length (1226.50 μm) and wall thickness (3.75 μm) and *Cecropia* sp the highest width (36.90 μm) and lume diameter (26.07 μm).

Our analysis has also considered the radial position from where the wood samples were removed (pith–bark direction; Table 4), in this scenario, it was observed a tendency of significant increase in the direction marrow – bark for *C. fissilis* and *G. americana*, which had different statistical values. The same propensity was not verified to *Cecropia* sp. Figure 3 brings models of radial variation of the parameters analyzed in the dimension of the fibers.

Concerning the average values of fiber width, greater values were observed for *Cecropia* sp. (36.9 μm), and posteriorly for *G. americana* (25.59 μm) and *C. fissilis* (25.17 μm) (Table 3). When compared as to the radial position of sample removal, there has not been seen significant increases in its dimensions, that is, the position of sample removal did not influence the values of fiber width, excepting by the position 0% (marrow) of *G. americana*, which showed shorter average value in comparison to those found for the other species (Table 4). The dimension of fiber width was a characteristic that had low variation degree, which may indicate that, apparently, it was little affected by the radial position of sample removal.

As for the lume diameter, the highest average value was observed for *Cecropia* sp. (26.07 μm), with *C. fissilis* (25.17 μm) and *G. americana* (8.06 μm) coming in next. When analyzing the radial position of sample removal, statistical differences were seen only for the position 0% (marrow) of *C. fissilis*, where fibers with higher average values of lume diameter were noticed (Table 4).

The last parameter analyzed was related to the fiber wall thickness, which is closely associated with the lume diameter. For this parameter, the highest average values were observed in *G. americana* (8.26 μm) and *Cecropia* sp. (5.41 μm), with *C. fissilis* presenting the lowest value (3.75 μm) (Table 3). Regarding the radial position of sample removal, *C. fissilis* had presented fibers with thicker walls in the outermost position (100%), near to the bark. This result was also observed for the fibers of *G. americana*, where the average values increased from the innermost part to the outermost part of the sample, thus providing an increase in the wall thickness of the fibers in the marrow – bark direction.

The average values of the indexes for the quality of the species' wood for the production of cellulose and its derivatives are presented in Table 5.

The results of the basic density of the *C. fissilis* was the closest one to those cited in the scientific literature for species and hybrids of *Eucalyptus* currently used for the production of cellulosic pulp in Brazil (Santos & Sansígolo 2007; Cherelli et al. 2018; Talgatti et al. 2020,) exhibiting the highest coefficient of variation among the species. The basic density values observed for the species in this

Table 2. Average values and coefficient of variation of the basic density for the species' wood. T – Tree identification; C.V. – coefficient of variation (%); A.V. - Average values; Average values followed by different letters, in the column, differ from each other by the Tukey test at 5% of significance.

Basic density (g.cm -3)								
Specie	T1	T2	T3	T4	T5	T6	C.V.	A.V.
Cedrela fissilis	0.43	0.33	0.35	0.40	0.46	0.52	17.02	0.42 b
Cecropia sp.	0.31	0.32	0.32	0.27	0.30	0.26	8.70	0.30 c
Genipa americana	0.56	0.54	0.62	0.56	0.57	0.60	5.13	0.58 a

Table 3. Average values (μm) of fiber's dimension of the three tree species. Average values followed by the same letter, in the line, do not differ from each other by the Tukey test at 5% of significance

Parameter (μm)	*Cedrela fissilis*	*Cecropia sp.*	*Genipa americana*
Length	1226.50 c	1270.53 b	1387.04 a
Width	25.17 b	36.90 a	24.59 c
Lume diameter	17.66 b	26.07 a	8.06 c
Wall thickness	3.75 c	5.41 b	8.26 a

research resemble those found by other authors, such as, de Mendoza et al. (2015), for the wood of *C. fissilis* (0.43 g.cm^{-3}) and Heckler et al. (2014) for the wood of *Cecropia* sp. (0.38 g.cm-3). Concerning *G. americana*, Jankowsky et al. (1990) and more recently, Iwakiri et al. (2017) reported values of 0.61 and 0.68 g.cm^{-3}, respectively.

The basic density affects significantly the cellulosic pulp quality. Studies show that higher pulp yields are achieved when utilized woods with basic density varying from 0.47 to 0.50 g.cm^{-3} (Gomes et al. 2015; Wille et al. 2021). Taking only this variable in consideration, the species *C. fissilis* and *G. americana* are the ones that best approaches the optimum range.

The differences in the average values of DBH between species – and also between trees of the same specie -, with identical age, indicates that they have a distinct secondary growth rate. This characteristic can influence the wood density, given that, increases in density may be directly proportional to the tree's diametrical growth, often associated with the age of the vascular cambium (Panshin & Zeeuw, 1980; Barrichelo & Brito, 1984).

It is known that the age of the individuals and the sampling position can influence the fiber length, as well as the climate conditions, the diversity of species and the variations within the same specie (de Miranda & Castelo 2012; Benites et al. 2015). Sette Jr. (2012) also says that, the increase of fiber length in function of the tree's age is a result of the increase in the length of the cells that originates them, denominated fusiform initials. The stabilization in the fiber length will occur when the cells of the cambium reach its maximum length, indicating the formation of adult wood (Rios 1987). Thus, the significant differences in average fiber length in the different radial positions may imply that the cambial meristem of these trees would be forming juvenile wood, taking in consideration the different rates of secondary growth of each specie addressed in this study.

The fiber length demonstrates to play influential effects on the superficial resistance and wet and dry resistance of papers, besides influencing the paper's tear. Fibers of shorter length provide better formation of the paper sheet and create papers with inferior physical-mechanical properties when compared to fibers of greater length (Benites et al. 2015; Vivian et al. 2022,).

The fiber width is a parameter used for calculating the coefficient of flexibility, so that, wider fibers may represent disadvantages in paper production, because it provides decreases in the bursting resistance (Foelkel et al. 1975). The behavior found in the species of this paper could be explained by the activity of the cambial zone, which produces wider fibers, with accentuated lume diameters. As in general, trees have an accelerated rate growth in the first 10 -12 years, this behavior tends to stagnate. Thusly, wider fibers with larger lume diameter are typically restricted to the internal region of the trunk, in other words, to the juvenile wood (Panshin & Zeeuw 1980; Barrichelo & Brito 1984).

There has not been cited in the literature a practical meaning for the lume diameter, however it is used for the determination of the fiber wall thickness (Brito, 2018). Fibers with thicker walls result in a smaller contact surface and poor fiber bonding, and consequently low collapsibility, which will originate papers with low quality (Benites et al. 2015). Gonçalez et al. (2014) studying the relationship between fiber dimension and wood basic density among the trunk of an 8 years old *Eucalyptus grandis* x *Eucalyptus urophylla*, have found average values of lume diameter well below the ones found in this research (5.59 μm), even so, its fibers showed positive characteristics to be used for pulp and paper.

Our results corroborate to what has been seen in the scientific literature in which, studies about the variability

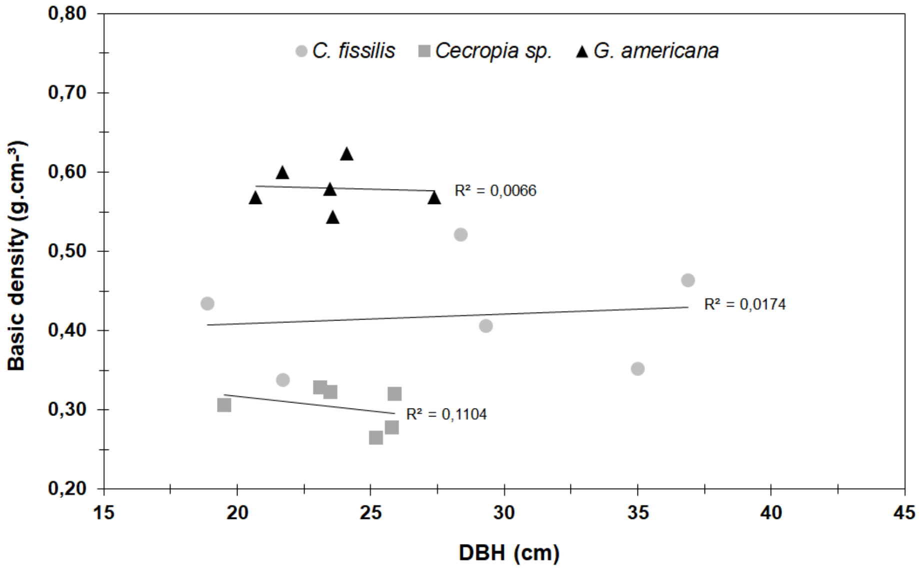

Figure 2. Relationship between basic density and diameter at breast height (DBH) among the species.

Table 4. Average values (μm) of fiber's dimension considering the radial position of samples' removal. Average values followed by the same letter, in the line, do not differ from each other by the Tukey test at 5% of significance

		Radial Position (%)		
Specie	**Parameter (μm)**	**0**	**50**	**100**
Cedrela fissilis	Length	1.108,77b	1.282,60a	1.288,12a
	Width	25.05a	24.92a	25.55a
	Lume diameter	18.29b	17.23a	17.45ab
	Wall thickness	3.38b	3.84a	4.04a
Cecropia sp.	Length	1.290.39a	1.244.78a	1.276.42a
	Width	37.85a	36.58a	36.27a
	Lume diameter	26.66a	26.45a	25.12a
	Wall thickness	5.59a	5.06b	5.57a
Genipa americana	Length	1.346.33b	1.359.47b	1.455.34a
	Width	23.60b	24.98a	25.19a
	Lume diameter	8.07a	8.25a	7.85a
	Wall thickness	7.76c	8.36b	8.67a

of wood characteristics have demonstrated certain biased behaviors of decrease or increase in wood properties in the marrow – bark direction (Cherelli et al. 2018). Yet, the same propensity has not been noticed for *Cecropia*'s sp. fibers (Table 4). The fiber wall thickness parameter is described as the one with the greatest contribution to the paper sheet properties, such as tensile strength, sheet density and air permeability. Foelkel and Barrichelo (1975) says that the fiber wall thickness when related to its width, predict fiber's rigidity during pulp and paper production.

Based on the obtained results, it is possible to suggest that the individuals of the species *C. fissilis* and *Cecropia* sp. have only juvenile wood, which is in general characterized as of low density, thinner cell wall and fibers of shorter length, among other characteristics. In the other hand, it can be implied that the wood of individuals of *G. americana* is in transition from juvenile to adult, or that it is already adult; once that the fiber's characteristics are contrary to *C. fissilis* and *Cecropia* sp. (de Avila Delucis et al. 2013; Trevisan et al. 2017; Albano 2022,). Nonetheless, for more precise information about the transition between juvenile to adult wood, it would be necessary to conduct studies regarding the microfibrilar angle and analysis in relation to this parameter.

The anatomical characteristics studied in this paper serve as a basis for the study of pulp and paper quality from native species. For example, the felting index establishes a relationship between the fiber length and width, being cited in the scientific literature as a variable associated with tear resistance (Rocha & Potiguara 2007; de Miranda & Castelo 2012; Nisgoski et al. 2012), and to bursting and double folds on papers (Salem et al. 2020) with values above 50 being desirable.

For this index, only *G. americana* surpassed the referential value (50.4), although the value observed for *C. fissilis* has been quite close (48.72). There has not been seen a common tendency of variation in the values among the species for the felting index in the marrow-bark direction. Benites et al. (2018) observed, in irrigated and Fertirrigated Eucalyptus hybrids that values were below to those reported which, according to the authors would result in papers of good tear resistance.

The coefficient of flexibility is the relationship between the lume diameter and fiber width, it is correlated to the fiber tensile strength (Rocha & Potiguara 2007), with higher values indicating greater fiber resistance at breaking and greater number of connections between fibers (interfiber connections) (Nisgoski et al. 2012). *C. fissilis* and *Cecropia* sp. showed close average values,

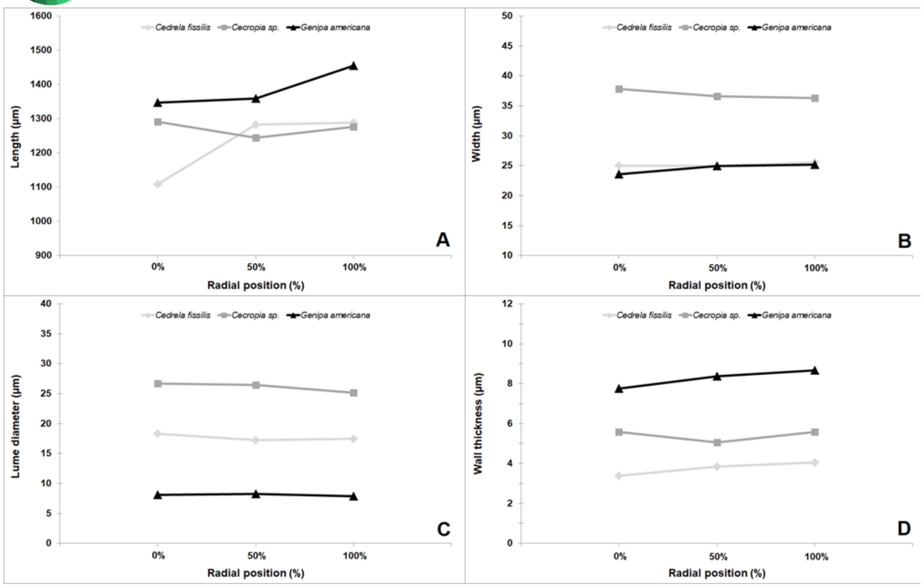

Figure 3. Models of radial variation of fiber's dimensions. A) Length; B) Width; C) Lume diameter; D) Wall thickness

Table 5. Average values of felting index (FI), coefficient of flexibility (CF), wall fraction (WF) and Runkel index (RI) of the studied species

	Parameters			
Species	**FI**	**CF (%)**	**WF (%)**	**RI**
Cedrela fissilis	48.72	70.16	29.79	0.42
Cecropia sp.	34.43	70.65	29.32	0.41
Genipa americana	56.40	32.77	67.18	2.04

70.16% and 70.65%; respectively, while *G. americana* had 32.77%. Even with the differentiation regarding the radial position, little variation was noticed, this could indicate that the variations on fiber width and lume diameter of the species was little important in the marrow – bark direction.

Foelkel and Barrichelo (1975) point out that the values obtained for *C. fissilis* and *Cecropia* sp. imply fibers partially collapsed, having thin cellular walls, with elliptical transversal section and good bond between fibers. Notwithstanding, for *G. americana* it is suggested that its fibers are quite thick and little collapsed, with limited contact surface and poor union between fibers.

Lower values as the ones observed for *C. fissilis* and *Cecropia* sp. were reported by Wate et al. (2018), in 5 species of *Eucalyptus* spp. with 5 to 9 years old which reinforces the inference that fibers with high values of coefficient of flexibility tends to increase the number of connections between fibers during the process of refining the cellulosic pulp, which will result in gains on the paper mechanical resistance. However, the same inferences do not apply to *G. americana*.

The wall fraction index is closely related to fiber rigidity, which directly influences the mechanical properties of the paper, as higher values indicate more rigid fibers. In accordance with the analysis, *C. fissilis* and *Cecropia* sp. had presented lower values, 29.79% and 29.32%, respectively, when compared to *G. americana* (67.18%). It was not observed tendencies of radial variation between the species; it was verified that higher values were noticed in the most peripheral position of the samples. This observation is due to the fact that fibers of the bark are generally wider and have thicker walls, thus creating greater rigidity.

The wall fraction values found for *C. fissilis* and *Cecropia* sp. are very close to those reported in studies with species of the genus *Eucalyptus*. Trugilho et al. (2005) found average value of 29.2% as they studied 15 different clones of *Eucalyptus* for the pulp and paper industry. These results evince that the fibers of both species (*C. fissilis* and *Cecropia* sp.) have good flexibility and therefore, good potential for this purpose.

Associated to the fiber rigidity, the scientific literature points the number 40 as a maximum value for the obtainment of high-quality cellulosic pulp (Foelkel & Barrichelo 1975). Fibers with higher values are extremely rigid and slightly flexible, making the connections between them more difficult and influencing the paper tear resistance (Rocha & Potiguara 2007; de Miranda & Castelo 2012; Nisgoski et al. 2012).

Lastly, there is the Runkel index, which evaluates the fiber collapse degree during the process of paper production. For this index, the values for *C. fissilis* and *Cecropia* sp. were respectively, 0.42 and 0.41, as for *G. americana* the value obtained was of 2.04. This results associate the first two species to the group II of Runkel, and puts *G. americana* in the group V.

Runkel (1952) proposed 5 groups for the evaluation of fibers, they are: group I (up to 0.25) considered as excellent for paper, group II (0.25 – 0.5) considered as very good, group III (0.5 – 1.0) considered as good, group IV (1.0 – 2.0) considered as regular and, group V (above 2.0) considered as not recommended for paper; taking in consideration the low degree of fiber collapsibility. The lower the index, the higher will be the collapse tendency which will allow the fibers to have a greater contact surface, higher number of connections between them and will result in papers with higher tensile strength and good burst resistance (Trevisan et al. 2017).

The average values for the Runkel index found in this research were, in general, lower than those observed in studies with *Eucalyptus*. Baldin et al. (2017) studying the wood anatomy and the potential for pulp and paper of young trees of four species of *Eucalyptus*, reported values varying from 0.72 to 1.07, which can subsidize, among the parameters evaluated in this research. The potential of native species as an alternative raw material to alien species in the production of cellulosic pulp and papers of good quality.

4. Conclusions

Of the three species studied, only *Cedrela fissilis* and *Cecropia* sp. met the desirable parameters and requirements of fiber dimensions and basic wood density for possible use to obtaining pulp and paper of good quality. However, to prove the real potential of the species for this purpose, it is fundamental to carry out complementary studies on: characteristics of the wood (chemical composition and other anatomical parameters), process and condition of formation of the pulp, and silvicultural aspects, such as the evaluation of the growth rate of the trees - represented mainly by the average annual increment -and its adaptation to different environmental conditions.

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