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WOOD POTENTIAL OF 33-YEAR-OLD *Corymbia citriodora* FOR PULP AND PAPER IN THREE SOIL TYPES[1]

POTENCIAL DA MADEIRA DE *Corymbia citriodora* DE 33 ANOS DE IDADE PARA PAPEL E CELULOSE EM TRÊS TIPOS DE SOLOS

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ABSTRACT - The pulp and paper industry is important to the Brazilian economy. In the present study, we investigated *Corymbia citriodora* wood in three soil types: Quartzarenic Neossol, Red Latosol and Red Nitosol. We aimed to determine how differences in physical, chemical and water-holding capacity among these three types of soils can cause changes in wood density and anatomical ratios in *C. citriodora* wood, important parameters in the production of pulp and paper. We used standard techniques in the methodology. Soil types did influence wood quality and could be used as a factor in considering the final quality of the product. *Corymbia citriodora* wood have not previously been considered for use in paper/pulp production. However, if we consider wood density as a key factor, wood from Red Nitosol - NV trees can be used since lower basic densities were identified and are most appropriate for the production of printing and writing paper, owing to fiber features. Otherwise, woods from Quartzarenic Neossol - RQ and Red Latosol - LV trees are more suitable for absorbent paper (tissue). We found that more clayey soil promotes lower basic density, and NV soil was found to be the most clayey of the studied soils. Based on nutritional information from soil, it appears that wood from LV soil trees would be the most suitable for present fewer problems in production. However, to be sure of this tentative conclusion, the contents of these nutrients would have to be analyzed in wood ash.

Keywords: Wood fibers; Quartzarenic neossol; Red latosol; Red nitosol; Wood density.

RESUMO - A indústria de celulose e papel é importante para a economia brasileira. No presente estudo, investigamos a madeira de *Corymbia citriodora* em três tipos de solo: Neossolo Quartzarênico, Latossolo Vermelho e Nitossolo Vermelho. Objetivamos determinar como as diferenças físicas, químicas e de retenção de água entre esses três tipos de solos podem causar alterações na densidade da madeira e nos parâmetros importantes na produção de celulose e papel de *C. citriodora*. Utilizamos técnicas padrão na metodologia. Os tipos de solo influenciaram na qualidade da madeira e poderiam ser usados como um fator a considerar na qualidade final do produto. A madeira de *C. citriodora* não foi considerada anteriormente para uso na produção de papel e celulose. No entanto, se considerarmos a densidade da madeira como um fator-chave, a madeira das árvores no Nitossolo Vermelho - NV pode ser usada, uma vez que densidades básicas mais baixas foram identificadas e são mais apropriados para a produção de papéis de impressão e escrita, devido às características das fibras. Enquanto que as madeiras das árvores no Neossolo Quartzarênico - RQ e Latossolo Vermelho - LV são mais adequadas para papel absorvente (tissue). Sugerimos que um solo mais argiloso proporciona menor densidade básica da madeira, e o solo NV foi considerado o mais argiloso entre os solos estudados. Com base nas informações nutricionais do solo, a madeira das árvores do solo LV seria a mais adequada por apresentar menos problemas na produção. No entanto, para ter certeza dessa conclusão experimental, o conteúdo desses nutrientes teria que ser analisado em cinzas de madeira.

Palavras-chave: Fibras de madeira; Neossolo quartzarênico; Latossolo vermelho; Nitossolo vermelho; Densidade da madeira.

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1 INTRODUCTION

The pulp and paper industry is important to the Brazilian economy. According to Bracelpa (2012), pulp had record performance in foreign markets, with Brazil standing out in global trade as the largest exporter of this product. These results can be explained by Brazil's high efficiency and competitiveness in pulp production, largely based on soil and climate conditions, as well as history of investment in forest research and development, as carried out by companies in the sector and by research agencies. Under these favorable conditions, national pulp production has been growing fast since the early 1990s (Hora, 2017). According to Bracelpa (2012), Brazil had a total of 7.83 million hectares in 2018 planted for industrial purposes. Thus, Brazil solidified its position as the world's second largest producer of cellulose pulp, behind only the USA. A total of 21.1 million tons of high-yield pulp were produced, including both short fiber from *Eucalyptus* and long fiber from *Pinus*.

Almost all pulp and paper preparations are made from wood of different species, and most of the raw material is from *Pinus* and *Eucalyptus* species (Foelkel, 2009; Hora, 2017). Wood pulp made from hardwood and softwood trees has different attributes. In Europe, hardwoods account for 29% and softwoods 71% of wood consumption (CEPI, 2019). *Eucalyptus* is one of the most used woods in the world for production of short fiber cellulose, and the most currently used species by their wood characteristics are *Eucalyptus grandis*, *Eucalyptus saligna*, *Eucalyptus urophylla*, *Eucalyptus viminalis*, hybrids of *E. grandis* x *E. urophylla* and *Eucalyptus dunnii* (southern region of Brazil). For the southern region, *Eucalyptus benthamii* is harvested owing to its tolerance to frost (EMBRAPA, 2020).

In spite of technological developments over the years and equipment used in paper production, suitability for use in pulp and paper production always comes down to variations in the wood (Foelkel, 2009). Thus, it is always necessary to discover and study new species, as well as study species already used in pulp/paper production, but under different conditions of growth and development, to establish germplasm banks or develop new production processes.

More than half of the paper used globally is for packaging, and this use has been increasing in recent years (FAO, 2016). Thus, studies are needed to confirm the quality of new materials to meet this particular demand. In this way, it is essential to study *Eucalyptus* and *Corymbia* species under different conditions in order to find new materials for pulp and paper production. In this context, we highlight *Corymbia citriodora* planted experimentally in units of the Forest Institute (Gurgel-Garrido et al., 1997).

To confirm the quality of wood for paper and cellulose production, several characteristics need to be investigated, including soil and climate conditions, type and planting management, tree growth and development, as well as such wood characteristics as density and cellular variations. According to Foelkel (2009), some essential characteristics for pulp and paper production are tree volume, wood density, the percentage of chemical constituents, such as extractives, lignin and holocellulose, and the characteristics and proportions of the cells that make up the wood.

Other essential data are obtained from knowledge about wood quality, in particular density, which is defined as the ratio of mass to volume expressed by the International System – IS in units of kilograms per cubic meter ($kg.m^{-3}$). Density is used to estimate mechanical properties (Hoadley, 2000), but it is also an important parameter for estimating wood quality as a raw material for the pulp and paper industry. In general, higher density is found in regions of adult wood compared to young wood, and according to Foelkel (2009), the latter has more appropriate characteristics for paper production. As determined by the Runkel Index, fiber characteristics, as obtained from fiber lumen dimensions and fiber wall thickness, are the best parameters for determining paper quality. Additionally, Horn (1978) reports that the Runkel index is a microscopic extension of wood density, precisely by using the fiber characteristics mentioned above. Thus, the study of anatomical variations is essential for understanding and choosing species for paper and pulp production. Differences in the characteristics of cells, parenchyma, vessels, and, especially, fibers, directly influence the quality of raw material for this purpose. Different quality indices can be calculated based on fiber features.

In the present study, we investigated the wood of *Corymbia citriodora* (Hook.), K.D. Hill, & L.A.S. Johnson (formerly *Eucalyptus citriodora* Hook.) in three soil types: Quartzarenic Neossol, Red Latosol and Red Nitosol. We aimed to determine how differences in physical, chemical and water-holding capacity among these three types of soils can cause changes in wood density and anatomical ratios for pulp and paper in *C. citriodora* wood.

2 MATERIAL AND METHODS

2.1 Provenances of the seeds, planting area and sampling

In 1982, *Corymbia citriodora* seeds of open-pollinated plants were collected in commercial plantations in Pederneiras State Forest, located in Pederneiras City, São Paulo State, Brazil (22°27′S, 48°44′W, elevation 500 m), categorized as CWa according to the Köppen climate classification scheme. In 1983, the progeny test was established with 56 progenies at the Luiz Antônio Experimental Station (LAES), Luiz Antônio City, São Paulo State (21o40'S, 47o49'W, elevation 550 m) (Gurgel-Garrido et al., 1997). According to CEPAGRI (2019), the average annual rainfall is 1,365 mm, and the average annual temperature is 21.7º C, with the warmest months occurring in January, February and March and the coldest months occurring in May, June and July.

The planting was established at a spacing of 3 m x 2 m, with one external border row of the same species, but without fertilization. The planting was installed with the same design in three different soil types, according to the LAES soil map (Rossi et al., 2016), by the Brazilian system of soil classification (SiBCS) (EMBRAPA, 2019). Site 1 has soil classified as Quartzarenic Neossol (symbol is RQ). Site 2 has Red Latosol (LV) soil, and site 3 is classified as Red Nitosol (NV). The correspondences among classes of SiBCS when compared to WRB/ FAO and Soil Taxonomy/USDA are RQ (arenosols / quartzipsamments), LV (ferralsols / oxisols) and NV (nitisols / Oxisols - Kandic) by EMBRAPA (2019).

In 2008, the LAES team determined height, DBH (Diameter at Breast Height - 1.30 m from the ground) and stem shape, using a grading system, with values ranging from one (worst grade, crooked trunks) to five (best grade, straighter trunks), and survival. In 2015, the LAES team conducted new growth, shape and survival analyses, but competition among the trees was added. The 2008 and 2015 information served as our basis for selecting 18 trees (one of each progeny, the same progeny in each soil type), the tallest and largest in diameter, for each type of soil, totaling 54 trees.

In 2016, we felled the selected trees, and from each tree, a log, 1 meter in length, was cut at the region immediately below the breast height. From logs, a central plank (5 cm thick) was cut, and from these planks, we cut three specimens in three radial positions: the nearest part of trunk center, designated as pith, a middle position, and a position close to the bark, designated as bark.

2.2 Soil sampling and analysis

We performed physical and soil water retention analysis according to EMBRAPA (1997) in undeformed samples. We collected samples at depths between 0–20 cm, three points within plantation, and then we mixed samples to prepare a composite sample. We repeated the same procedure for each soil type. For texture analysis, we determined the percentages of sand, clay and silt. We also determined soil water retention content and soil bulk density with volumetric cylinder, using three samples of each soil type.

Air-dried soil samples were analyzed for Phosphorus (P); Aluminum (Al); H+Al; Aluminum Saturation (m%); basic cations, including Potassium (K), Calcium (Ca), and Magnesium (Mg); sum of the bases Ca, Mg and K (SB); pH; base saturation (V%); the micronutrients Boron (B), Copper (Cu), Iron (Fe), Manganese (Mn) and Zinc (Zn); Cation Exchange Capacity (CEC); and total Organic Carbon (O.M.). Chemical soil analysis was carried out according to Raij et al. (2001).

2.3 Basic density

Basic density was determined by finding the ratio between dry mass and saturated volume. The specimens (5 cm x 3 cm x 2 cm) were immersed in water and were considered saturated when they presented constant mass during monitoring in the laboratory. Subsequently, the specimens were dried in an oven at 105°C ± 2°C to obtain the dry mass. Saturation volume was obtained by the hydrostatic balance method. Wood basic density was calculated by determining the relationship between dry mass and saturated volume in accordance with the Brazilian standard ABNT NBR 11941 (ABNT, 2003).

$$\rho bas = \frac{Dm}{Sv}$$

where ρbas = basic density ($kg.m^{-3}$), *Dm* = Dry mass (kg) and *Sv* = Saturated Volume (m^{-3}).

2.4 Anatomical analyses

We cut small pieces of wood from each sample for maceration using Franklin's method (Berlyn e Miksche, 1976). Wood fragments were stained with aqueous safranin 1% and mounted temporarily in a solution of water and glycerin (1:1). Samples of 2 cm^3 were softened in boiling water and glycerin (4:1) for 1 hour. From these samples, transverse sections 20μm in thickness were obtained with a sliding microtome. Sections were bleached with sodium hypochlorite (60%), washed thoroughly in water, and stained with 1% safranin (Johansen, 1940).

Measurements followed the recommendations of the IAWA (1989). Quantitative data were based on at least 25 measurements for each feature from each tree, thus fulfilling statistical requirements for the minimum number of measurements. The proportions of fibers, vessels, axial parenchyma and rays in the transverse sections were measured using a 25-point grid for each sample. Anatomical measurements were obtained using an Olympus CX 31 microscope equipped with a camera (Olympus E330 EVOLT) and computer image analysis software (Image-Pro 6.3).

2.5 Anatomical ratios for pulp and paper

From values of Length (L), Diameter (D), lumen diameter (d) and fiber wall thickness (w), we calculated the following ratios for pulp and paper: Flexibility Coefficient (FC), Wall Proportion (WP), Runkel Ratio (RR), Slenderness Ratio (SR), and Luce's Shape Factor (LSF) (Pirralho et al., 2014).

$$FC = \frac{d}{D}$$

$$WP = \frac{2.w}{D} \times 100$$

$$RR = \frac{2.w}{d}$$

$$SR = \frac{L}{D}$$

$$LSF = \frac{D^2 - d^2}{D^2 + d^2}$$

2.6 Data analyses

We initially undertook descriptive statistical analysis and used Box Plot graphics to detect outliers. Thus, values 1.5 times higher than the 3rd quartile and values 1.5 times lower than the 1st quartile were excluded from the analysis. Normality tests were performed to check the distribution of data, and when a normal distribution was not observed, data were square root-transformed. Then, a parametric analysis of variance (one-way analysis of variance (ANOVA)) was performed. When a significant difference was observed, Tukey's test was used to identify pairs of significantly different means. We analyzed the radial variation within the same tree and also three radial positions together, comparing the results in three soil types.

3 RESULTS

According to granulometry analyses, the three soil types are reflective of different textures. RQ is classified sandy texture and has 52% coarse sand, 41% fine sand, 4% clay and 3% silt. LV is medium texture and has 40% coarse sand, 41% fine sand, 16% clay and 3% silt. NV is clayey texture and presented the lowest amount of coarse sand (6%), fine sand (13%) and the largest amount of clay (52%) and silt (29%) (Table 1).

For chemical attributes, we observed differences in pH, organic matter, macronutrient and micronutrient, as well as base saturation. We noticed the most acidic pH in LV, and we noticed higher organic matter in NV. LV and RQ had high Al^{3+}, but phosphorus, potassium, calcium and magnesium had low values. Sulfur has average reference values for all three soil types. On the other hand, significant differences were observed for micronutrients. LV and RQ had lower values, and NV had higher values. In all soils, we found high levels of iron and low values manganese and zinc for LV and RQ. NV had high values for all macronutrients and micronutrients. According to the reference values, base saturation (V%) was very low for LV and RQ, but in the mid-range for NV soils (Table 2). RQ had higher soil density, while NV had lower density and higher retained water (Table 3).

Table 1. Physical attributes of three soil types (0-20 cm layer) of 33-year-old *Corymbia citriodora* plantings.

Tabela 1. Atributos físicos dos três tipos de solos (camada 0-20 cm) do plantio de *Corymbia citriodora* de 33 anos de idade.

Soils	Sand			Clay	Silt	Soil texture
	Coarse	Fine	Total ($g.kg^{-1}$)			
RQ	516	415	930	43	27	Sand
LV	399	413	812	158	30	Sandy loam
NV	65	130	195	519	286	Clay

Quartzarenic Neossol - RQ; Red Latosol - LV; Red Nitosol - NV.

Neossolo Quartzarênico - RQ; Latossolo Vermelho - LV; Nitossolo Vermelho - NV.

Table 2. Chemical attributes of the soil of the 33-year-old *Corymbia citriodora* plantation in three types of soils (0-20 cm layer).

Tabela 2. Atributos químicos do solo do plantio de *Corymbia citriodora* de 33 anos de idade em três tipos de solos (camada 0-20 cm).

	pH	O.M	P	Al^{3+}	H+Al	K	Ca	Mg	S	SB	CEC	m%	V%	B	Cu	Fe	Mn	Zn
Soils	$CaCl_2$	$g.dm^{-3}$	$mg.dm^{-3}$	------------$mmol_c.dm^{-3}$------------										----------$mg.dm^{-3}$----------				
RQ	4.1	7	3	6	29	0.4	2	1	7	3	32	64	9	0.15	0.2	88	0.5	0.1
LV	3.8	10	4	10	56	0.4	2	1	6	3	59	75	5	0.20	1.4	68	0.9	0.1
NV	4.6	24	96	1	92	6.1	62	13	7	81	173	1	47	0.26	14.6	49	94.8	4.4

Quartzarenic Neossol - RQ; Red Latosol - LV; Red Nitosol - NV. Total Organic Carbon (O.M); Phosphorus (P); Aluminum (Al); H+Al; Potassium (K); Calcium (Ca); Magnesium (Mg); Sulfur (S); Sum of the Bases Ca, Mg and K (SB); Cation Exchange Capacity (CEC); Aluminium Saturation (m%); Base Saturation (V%); Boron (B); Copper (Cu); Iron (Fe); Manganese (Mn) and Zinc (Zn).

Neossolo Quartzarênico - RQ; Latossolo Vermelho - LV; Nitossolo Vermelho- NV. Matéria Orgânica Total (O.M).; Fósforo (P); Alumínio (Al); H+Al; Potássio (K); Cálcio (Ca); Magnésio (Mg); Enxofre (S); Soma das Bases Ca, Mg e K (SB); Capacidade de Troca Catiônica (CEC); Saturação de Alumínio (m%); Saturação de Base (V%); Boro (B); Cobre (Cu); Ferro (Fe); Manganês (Mn) e Zinco (Zn).

Table 3. Average retained water and soil density of 33-year-old *Corymbia citriodora* plantation in three soil types (0-20 cm layer).

Tabela 3. Média de retenção de água e densidade do solo de plantio de *Corymbia citriodora* de 33 anos de idade em três tipos de solos (camada 0-20 cm).

Retained water ($dm^3.dm^{-3}$)									
Tension (MPa)									Soil density
Soils	Saturated	0.003	0.006	0.01	0.03	0.1	0.5	1.5	($kg.dm^{-3}$)
RQ	0.43	0.33	0.22	0.13	0.09	0.07	0.06	0.05	1.85a
LV	0.53	0.39	0.29	0.19	0.14	0.12	0.10	0.10	1.70b
NV	0.63	0.47	0.44	0.38	0.33	0.31	0.29	0.29	1.51c

Quartzarenic Neossol - RQ; Red Latosol - LV; Red Nitosol - NV.

Neossolo Quartzarênico - RQ; Latossolo Vermelho - LV; Nitossolo Vermelho - NV.

We observed a gradual increase of wood density from the pith to the bark in LV and NV soils, whereas in RQ soil, pith showed lower density, and no significant difference was noted between intermediate and bark positions. Among soil types, we observed lower density in NV, and no significant differences were seen between LV and RQ (Table 4).

We found a gradual increase in pith-to-bark direction for fiber length in the three soil types. Fibers with larger diameter occur in bark. Fiber lumen diameter gradually decreased toward the bark in the three soil types. Fiber wall thickness increased gradually from pith-to-bark in the three soil types. Longer fibers with larger diameter and larger lumen diameter occurred in NV, and smaller diameter fibers occurred in LV. Thicker wall fibers occurred in RQ (Table 4).

Flexibility coefficient gradually decreased from pith-to-bark in the three soil types. Wall proportion, RR and LSF all increased from pith-to-bark in the three soil types. While SR showed lower values in pith, it showed higher values and no difference in intermediate and bark positions, respectively (Table 4).

Among the soil types, flexibility coefficient was higher in NV. Wall proportion showed no differences between LV and RQ soils, but a lower value could be observed in NV. RR was higher in RQ and lower in NV. Slenderness ratio was higher in LV, and no difference was observed between RQ and NV soils. Luce's shape factor was lower in NV (Table 4).

Table 4. Radial variation of density and ratios for pulp and paper in 33-year-old *Corymbia citriodora* wood in three soil types.

Tabela 4. Variação radial da densidade e taxas de papel e celulose na madeira de *Corymbia citriodora* de 33 anos de idade em três tipos de solos.

	Quartzarenic Neossol				Red Latosol				Red Nitosol			
	Pith	Inter	Bark	mean	Pith	Inter	Bark	mean	Pith	Inter	Bark	mean
WD	0.85b	0.93a	0.95a	0.91A	0.82c	0.93b	1.01a	0.92A	0.80c	0.85b	0.95a	0.87B
FL	947c	989b	1037a	991B	901c	1014b	1071a	995B	905c	1065b	1099a	1023A
FD	15.5b	15.3b	16.2a	15.7B	14.8b	14.9b	15.4a	15.0C	16.0b	16.4b	17.0a	16.5A
FLD	4.8a	3.3b	2.7c	3.6B	4.4a	3.5b	2.9c	3.6B	6.1a	4.7b	4.0c	4.9A
FWT	5.3c	5.9b	6.7a	5.7B	5.2c	5.7b	6.2a	5.7B	4.9c	5.8b	6.5a	6.0A
FC	30.29a	21.37b	16.59c	22.75B	28.92a	22.86b	18.80c	23.52B	37.45a	28.36b	23.05c	29.62A
WP	69.70c	78.62b	83.40a	77.24A	71.07c	77.13b	81.20a	76.47A	62.54c	71.63b	76.94a	70.37B
RR	3.03c	4.68b	6.04a	4.58A	3.01c	4.34b	5.07a	4.14B	2.09c	3.38b	4.23a	3.23C
SR	62.55b	65.81a	65.66a	64.67B	62.69b	69.22a	71.11a	67.67A	58.03b	66.37a	66.16a	63.52B
LSF	0.81c	0.90b	0.93a	0.88A	0.83c	0.88b	0.92a	0.88A	0.74c	0.83b	0.88a	0.82B

In the same row, distinct letters differ statistically (P <0.05) by Tukey test. Pith = Wood near the Pith. Inter = Wood of Intermediate position. Bark = Wood next to the Bark. M = Mean between radial positions. Lowercase letters for differences between radial positions and uppercase letters for differences between soil types. WD = Wood Density ($g.cm^{-3}$); FL = Fiber Length (µm); FD = Fiber Diameter (µm); FLD = Fiber Lumen Diameter (µm); FWT = Fiber Wall Thickness; FC = Flexibility Coefficient; WP = Wall Proportion (%); RR = Runkel Ratio; SR = Slenderness Ratio; LSF = Luce's Shape Factor.

Na mesma linha, letras distintas diferem estatisticamente (P <0,05) pelo teste de Tukey. Medula = Madeira perto da Medula. Inter = Madeira de posição Intermediária. Casca = Madeira próxima à Casca. M = média entre as posições radiais. Letras minúsculas para diferenças entre posições radiais e letras maiúsculas para diferenças entre tipos de solo. WD = Densidade da Madeira ($g.cm^{-3}$); FL = Comprimento da Fibra (µm); FD = Diâmetro da Fibra (µm); FLD = Diâmetro do Lúmen da Fibra (µm); FWT = Espessura da Parede da Fibra; FC = Coeficiente de Flexibilidade; WP = Fração Parede (%); RR = Índice de Runkel; SR = Índice de Esbeltez; LSF = Fator de Forma de Luce.

Fiber percentage increased gradually from the pith to the bark in RQ. In LV and NV, fiber percentage was higher in intermediate and bark positions. Vessel percentage did not vary in radial positions in the three soil types. Axial parenchyma percentage increased gradually from the pith to the bark in RQ and was higher in pith in LV and NV. Radial parenchyma percentage in RQ soil was higher in intermediate and bark positions, but decreased from pith to bark in LV, not varying at all in radial positions in NV (Figure 1). When considering the three positions together, we observed differences in vessel percentages, higher in RQ, and radial parenchyma, higher in LV and NV (Figure 2).

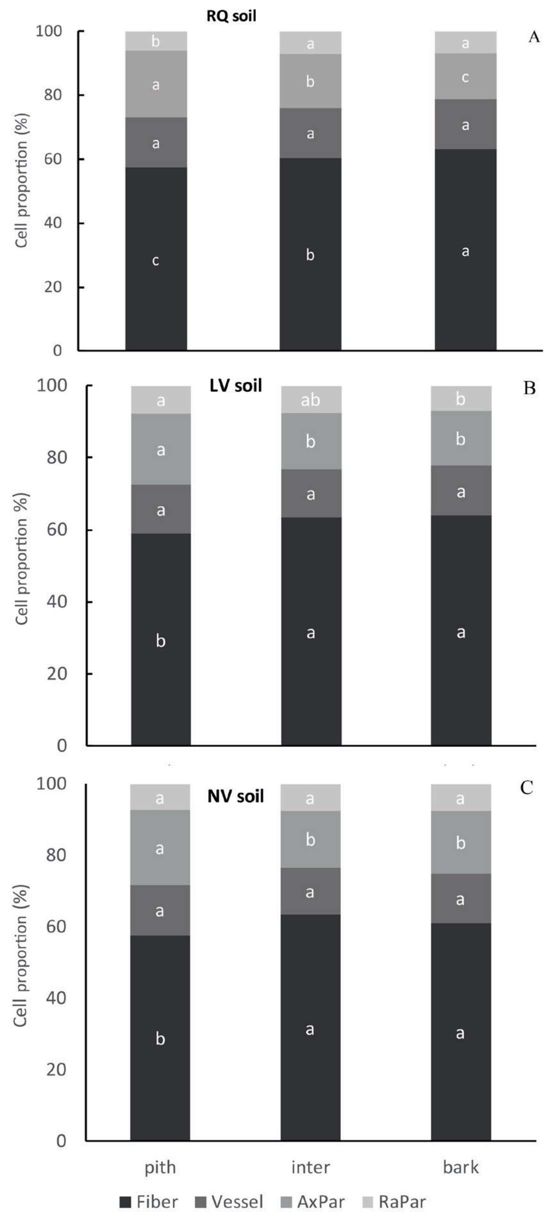

Figure 1. Proportion of cells in 33-year-old *Corymbia citriodora* wood in three soil types. Pith = Wood near the Pith. Inter = Wood of Intermediate position. Bark = Wood next to the Bark. Quartzarenic Neossol - RQ; Red Latosol - LV; Red Nitosol - NV.

Figura 1. Proporção de células da madeira de *Corymbia citriodora* de 33 anos de idade em três tipos de solo. Medula = Madeira perto da Medula. Inter = Madeira de posição Intermediária. Casca = Madeira próximo a Casca. Neossolo Quartzarênico - RQ; Latossolo Vermelho - LV; Nitossolo Vermelho - NV.

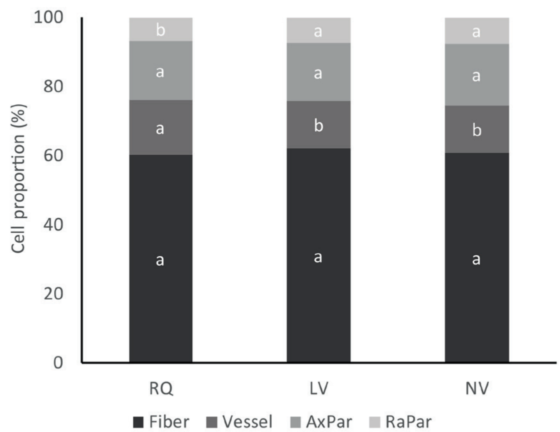

Figure 2. Proportion of cells in 33-year-old *Corymbia citriodora* wood in three soil types. Quartzarenic Neossol - RQ; Red Latosol - LV; Red Nitosol - NV. In each soil, the values are mean between radial positions.

Figura 2. Proporção de células da madeira de *Corymbia citriodora* de 33 anos de idade em três tipos de solo. Neossolo Quartzarênico - RQ; Latossolo Vermelho - LV; Nitossolo Vermelho - NV. Em cada solo, os valores médios são entre as posições radiais.

4 DISCUSSION

Wood density followed the pattern commonly reported in the literature, increasing toward the bark. Among soil types, wood from NV trees presented the lowest density, which is theoretically linked to highest quality for pulp and paper. Santos and Sansígolo (2007) and Mokfienski et al. (2008) report that pulps from wood with lower basic densities are ideal for production of printing and writing paper, owing to fiber features, *e.g.*, fibers with thinner walls. Thus, if we use density to choose raw material, wood from NV, as described in our study, would, potentially, be more appropriate for the production of printing and writing paper. However, wood from NV has longer fibers with larger diameter, larger lumen diameter and wall thickness. Although fibers, in percentage terms, are the cells most present in wood, (Baas et al., 2004; Lachenbruch et al., 2011), we must consider the characteristics of other cells and their proportions. Otherwise, pulps from denser woods are ideal for absorbent paper, owing to fibers with thicker walls (Santos e Sansígolo 2007; Mokfienski et al., 2008). In this context, wood from RQ and LV soils are more suitable for absorbent paper (tissue) based on higher density compared to wood from NV soil. However, wood samples from the first two soil types have thinner wall fibers compared to wall fibers from NV but showed a higher wall proportion in both soils.

Sansígolo and Ramos (2011) studied approximately 4-year-old *Eucalyptus grandis* planted in three different fertile soils and compared trees from less fertile soils to trees from more fertile soils. Trees in the former category tended to have higher wood density, higher total and screened yields from pulping, lower specific wood consumption of pulp, and higher tear and tensile indices at low refining levels. The results corroborate those of our study in which lower wood density was found in the more fertile NV soil. Wood density is positively correlated with fiber flexibility coefficient. According to Saikia et al. (1997), wood with good flexibility values are suitable for production of paper with high mechanical resistance, such as writing, printing and packaging. Therefore, we suggest that NV soil with highest FC value has good potential for meeting these demands.

Studying the influence of soil on the quality of *Pinus taeda* wood for production of kraft pulp, Rigatto et al. (2004) found that wood from places with more clayey soil had lower basic density. We found the same result for *C. citriodora* since tree wood from NV soil, which is the most clayey of the three soils, presented lower density, showing that even in very different species (*P. taeda* and *C. citriodora*), a negative relationship seems to arise between soil clay content and wood density. Clayier soils tend to retain more water than sandy soils, these environmental conditions can favor a decrease in wood density due to increased cambial activity. The vascular cambium in these favorable conditions can produce fibers and vessels with greater frequency and diameter and with thin cell wall (Castro et al., 2020).

Studying the effect of *E. grandis* wood density on papermaking, Cremonez et al. (2019) concluded that increase in wood density did not promote variations in pulp yield, considering the same cooking conditions. However, denser wood had lower specific consumption, making it difficult to ignite and, hence, impairing selectivity of the pulping process. From this point of view, wood from NV trees would be more suitable for papermaking owing to lower density.

Soil chemical composition can also influence the production process and, consequently, paper quality. TAPPI (2006) describes difficulties in paper processing that can arise because of the presence or the excess of certain nutrients in wood. In our study, we did not perform ash assessments, so results are estimated based on the presence of these nutrients in the soil. According to TAPPI (2006), calcium in dissolving pulps can cause difficulties in viscose spinning and film casting operations. Copper may interfere with the color of dyes to be used in the pulp, have an adverse effect on paper permanence, and affect dissolving pulp quality. Manganese in pulp acts as a catalyst in oxidizing cellulose; i.e., it adversely affects paper permanence. NV soil has much more calcium, copper and manganese than the other two soil types based on the soil nutritional information, suggesting that wood from NV trees could present more problems during paper production. Iron in pulp can cause discoloration and problems in photographic and blueprint papers, as well as have an adverse effect on paper permanence and affect dissolving pulp quality. In this case, RQ showed the highest iron content and NV the lowest. Based on nutritional information from soil, it appears that wood from trees in LV soil would be most suitable for present fewer problems in production, but to be sure of this result, the contents of these nutrients would have to be analyzed in wood ash.

We evaluated flexibility coefficient and found a value of 0.37 in pith position in NV. This is classified as a thick wall type, in which fibers collapse very little and have little contact surface with little union between fibers. In all other positions, values were below 0.30, which means very thick wall type, in which fibers do not collapse and have very little contact surface with poor union between fibers. According to Bektas et al. (1999) flexibility coefficients between (50-75%) are considered elastic fibers, ideal for paper production and flexibility coefficients below 30% are considered highly rigid fibers, not suitable for paper production.

In wall proportion, the higher this index, the more rigid and resistant to collapse fibers will be (Foelkel, 2009). In this case, wood fibers in RQ and LV trees had higher values than those of NV. However, paper with poor flexibility originating from fibers with very high wall proportion values tends to have lower tensile and burst strength (Boschetti et al., 2015).

Fibers with higher RR values are stiffer and less flexible (Ogunjobi et al., 2014), and they produce more porous papers compared to lower RR fibers (Kiaei et al., 2014). The lowest RR value was observed in NV; however, it is suggested that values above 2 are classified in grade 5, characterizing low-quality material for papermaking (Foelkel, 2009).

According to Agnihotri et al. (2010), SR interferes with paper density and tear resistance. This index is also directly related to pulp digestibility (Ohshima et al., 2005). In our study, we observed the highest SR value in LV.

Luce's form factor is also related to final density of paper sheet, and it may be a property used in species selection for wood quality for paper and pulp (Baldin et al., 2017). The authors studied different paper quality indices in four *Eucalyptus* species and found lower values than those of *C. citriodora*, even compared with pith position values (0.81 in RQ), which represents young wood from the studied trees. The values found for Luce's form factor for *C. citriodora* are considered high values. The Luce form factor may be related to the wall thickness, due to the fiber diameter and fiber lumen diameter being used in the equation for the Luce's form factor (Ohshima et al., 2005). Luce's form factor values reported in several studies for *Ecalyptus* species most used for pulp and paper as *E. grandis* (0.50) and *E. saligna* (0.49) (Baldin et al., 2017), *E. camaldulensis* (0.51) (Pirralho et al., 2014), *E. camaldulensis* (0.39, 0.37) and *E. globulus* (0.40, 0.47) (Ohshima et al., 2005). The authors mention these values as means.

In *Pinus taeda* wood, Rigatto et al. (2004) report shorter, wider and thinner-walled tracheids in more clayey soils. In *C. citriodora*, we observed longer, wider and thicker-walled fibers in wood from NV trees (more clayey soil in our study). Despite being from different plant groups, in the absence of other studies with same plant group, *Pinus* and *Corymbia* comparison can give an idea of results.

As previously noted, fibers are cells that mostly occur in wood (Baas et al., 2004; Lachenbruch et al., 2011), and they are certainly those cells that most influence pulp and paper quality. However, other cells, vessels and parenchyma also influence paper material quality. Fragments of cell walls of fibers or other cells, as well as whole vessel and parenchyma cells, and other debris are often referred to as fines. These fines cause problems during pulping and refining, as well as further pulp processing (Foelkel, 2009), with high quality pulps having lower fines (Fengel e Wegener, 1989). Counting the percentage of each cell type, fiber, vessel, or parenchyma is a way of estimating fines content.

When analyzing different radial positions, it would be obvious to consider wood from intermediate and bark position as lower quality for paper since in paper and pulp production, young trees are used. However, when analyzing the results in the three soils, we reported higher percentages of fibers from intermediate position to the bark. In addition, we found a larger proportion of axial parenchyma in the pith, representing the youngest wood that, theoretically, could be used in paper production. However, we saw a higher proportion of radial parenchyma in intermediate and bark positions in RQ and lower proportion in pith in LV. When analyzing the three positions together, such values complicate establishing quality by the higher proportion of vessels and lower proportion of radial parenchyma in pith. In general, it is desirable that woods present a lower fines content.

According to Foelkel (1997), papers have specific characteristics according to purpose. For example, in printing and writing papers, smoothness, opacity, formation, volume, porosity, printability, resistance, and dimensional stability are desirable. Such characteristics are obtained with a higher percentage of short and narrow fibers, with relative rigidity and good refinability, capable of holding together without collapsing, constituting a well-structured network, with good connection between fibers and low content of vessel elements. Otherwise, still according to Foelkel (1997), in sanitary papers (tissue), the desired properties are softness, softness to the touch, absorption, sensation of soft and bulky paper, resistance, low content of fines. Such characteristics are obtained with rigid fibers and with a low degree of collapsibility to resist embossing and creping, narrow fibers, low hemicellulose content and relative resistance to refining, low parenchyma cell content, low connection between fibers, maintaining a loose network and porosity.

5 CONCLUSIONS

Previously a neglected species, *Corymbia citriodora* have attracted more interest for pulp and paper production. If we consider wood density, wood from Red Nitosol - NV trees can be used since lower basic densities are most appropriate for production of printing and writing paper, owing to fiber characteristics. Otherwise, woods from Quartzarenic Neossol - RQ and Red Latosol - LV trees are more suitable for absorbent paper (tissue). As for soil physical composition, more clayey soil promotes lower basic density, which occurred in NV soil, having the most clayey soil among the three studied soils. Based on nutritional information from soil, it appears that wood trees from the LV soil would be most suitable for present fewer problems in production, but to be sure of this result, the contents of these nutrients would have to be analyzed in wood ash. Quality index and proportion of cells also varied, and wood choice depends on the type of paper desired. In summary, soil types did influence wood quality and could be used as a factor in determining the final quality of the product.

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