Kraft pulping and papermaking of *Cryptomeria japonica*Polpação Kraft e produção de papel de *Cryptomeria japonica*

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Abstract

Cryptomeria japonica is a softwood of Japanese origin known for its versatility wood use. The objective of this work was to characterize the wood of *C. japonica* for kraft pulping and papermaking. For this, wood chips from a 13-year-old trees of *C. japonica* and, as reference material, industrial wood chips of *Pinus taeda*, both from southern Brazil was used. The physical, chemical, fiber dimensions of the woods, the performance of each species in the kraft pulping and the paper physico-mechanical properties was evaluated. The fiber size, wood basic density, extractive content, and holocellulose content of *C. japonica* were lower than those of *P. taeda*, on the other hand total lignin and ash in wood were higher. On kraft pulping the performance of the *C. japonica* wood was superior, with better yields, lower reject content and lower active alkali consumption, despite requiring more active alkali to achieve the desired kappa and presenting higher specific wood consumption. The papers made with the *C. japonica* pulp presented superior physico-mechanical properties.

Keywords: Long fiber pulp, softwood, unbleached pulp.

Resumo

Cryptomeria japonica é uma conífera de origem japonesa conhecida pelo uso versátil de sua madeira. O objetivo deste trabalho foi caracterizar a madeira de *C. japonica* para a polpação Kraft e para a fabricação de papel. Para tanto, foi utilizado uma amostra de cavacos de madeira de *C. japonica* com 13 anos de idade e, como material de referência, cavacos industriais de madeira de *Pinus taeda*, ambos do sul do Brasil. A avaliação considerou as propriedades físicas, químicas, as dimensões dos traqueídeos das madeiras, o desempenho de cada espécie na polpação Kraft e as propriedades físico-mecânicas dos papéis. As dimensões das fibras, a densidade básica da madeira, o teor de extrativos e o teor de holocelulose de *C. japonica* foram menores que os de *P. taeda*, enquanto a lignina total e as cinzas presentes na madeira foram maiores. Na produção de celulose Kraft o desempenho da madeira de *C. japonica* foi superior, com melhores rendimentos, menor teor de rejeitos e menor consumo de álcali ativo, apesar de necessitar de maior carga alcalina para atingir o kappa desejado e apresentar maior consumo específico de madeira. Os papéis feitos com a polpa de *C. japonica* apresentaram propriedades físico-mecânicas superiores.

Palavras-chave: Celulose de fibra longa, conífera, polpa não branqueada.

INTRODUCTION

The Brazilian forestry sector is a worldwide reference in terms of productivity. It is promoted by the expansion in the investments in innovation and technology, providing high competitiveness for the country. According to IBÁ (2018), Brazil has 7.84 million hectares of planted forests, which corresponds less than 1% of the total country area and it is responsible for 6.1% of the Gross Domestic Product (GDP) by Industry. Another indicator of competitiveness is the Brazilian Trade Balance that reached +US\$ 9.0 billion (IBÁ, 2018).

Considering the pulp and the paper sector, Brazil is the second largest pulp producer in the world, with 19.5 million tons (up 3.7% over the previous year), and the eighth in paper production

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(up 1.9% over the previous year) (IBÁ, 2018). Including the pulp production managed in the foreign market, Brazil is the third largest exporter of pulp (COELHO JÚNIOR et al., 2018).

Looking at this positive scenery, there is a demand for the search of new technologies and alternative species with potential for the “short fiber” and “long fiber” segments. Considering the context, the *Cryptomeria japonica* species appear to be suitable for the “long fiber” segment for being a conifer of the *Cupressaceae* family.

C. japonica is a native species from Japan, it is known as “sugi” and there are great utilities. Its wood has physical characteristics providing good workability. It is widely used in industries for sawn timber, wood panel, furniture, pulp and paper production (PEREIRA et al., 2003). In Brazil, the species is commonly known as “cedrinho japonês” and it was introduced by “Companhia Melhoramentos”, specially in Caieiras city in São Paulo state as also in Camanducaia in the Mantiqueira Mountains in Minas Gerais state (CARNEIRO et al., 2009).

In general, the cultivation of the species has a high potential in the South of Brazil: fast growth, easy adaptation to the climate and soil conditions and good response to silvicultural treatments (PEREIRA et al., 2003). Carvalho (2001) reported that for the present species, there is an average annual increment (IMA) of wood up to $45 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{ano}^{-1}$, in case of optimal sites in Santa Catarina state.

However, despite of the high economic potential, there are not studies for the *C. japonica* species about the suitability of the wood in chemical conversion processes; the cellulosic pulp is one example. The explanation is that in Brazil, the genus *Pinus* is widely used and consolidated for the “long fiber” segment, making the entrance difficult for the new species of conifers. Therefore, it is necessary to evaluate other species that may be an alternative to this problem in the near future. Thus, the aim of this paper is to evaluate the quality of the *C. japonica* wood for pulping and paper production.

MATERIAL AND METHODS

Wood origins

To conduct the present study, it was used wood chips of *Cryptomeria japonica* from a 13-years-old experimental forest planting in Campo Belo do Sul city in Santa Catarina state, Brazil, $27^{\circ}53'57'' \text{ S } 50^{\circ}45'39'' \text{ W}$ WSG84 coordinates as also as reference material, industrial wood chips of *Pinus taeda* from Telêmaco Borba city in Paraná state, Brazil, $24^{\circ}19'26'' \text{ S } 50^{\circ}36'57'' \text{ W}$ WSG84 coordinates.

To prevent the circulation of chemical reagents and the impregnation in the pulping process, the wood chips were submitted to a thickness control between 4 and 6 mm.

Wood characterization

The wood basic density was determined by the mass weighing method and the indirect volume measurement according to the TAPPI T 258 om-16 (TAPPI, 2016a), standard in five samples of 100 grams per species.

The tracheids dimensions were obtained according to the guidelines of the International Association of Wood Anatomy (IAWA, 1989). The length, width and lumen diameter of one hundred tracheids per species were measured. The wall thickness and the wall fraction were calculated according to equations 1 and 2.

$$WT = \frac{FW - LD}{2} \quad (1)$$

Equation 1. WT is the wall thickness (μm); FW is the tracheids width (μm); LD is the lumen diameter (μm).

$$WF(\%) = \frac{2 \cdot WT}{FW} \cdot 100 \quad (2)$$

Equation 2. WF is the wall fraction (%); WT is the wall thickness (μm); FW is the tracheids width (μm).

The sampling and the preparation of wood for chemical analysis were made according to TAPPI T 257 sp-14 (TAPPI, 2014) in five samples per species. At this point, it was determined the total extractive content (TAPPI T 204 cm-17) (TAPPI, 2017), the insoluble lignin content (TAPPI T 222 om-15) (TAPPI, 2015a), the soluble lignin content (GOLDSCHIMID, 1971) and the inorganic ash content (TAPPI T 211 om-16) (TAPPI, 2016b). The total lignin and the holocellulose contents were calculated according to equations 3 and 4.

$$LT(\%) = IL(\%) + SL(\%) \quad (3)$$

Equation 3. LT is the total lignin content (%); IL is the insoluble lignin content (%); SL is the soluble lignin content (%).

$$\text{Holo}(\%) = 100 - (\text{LT}(\%) + \text{TE}(\%)) \quad (4)$$

Equation 4. Holo is the holocellulose content (%); TE is the total extractive content (%).

Kraft pulping

The conventional kraft batch cooking was performed in a rotary autoclave containing four individual stainless steel capsules with a capacity of 1600 mL each. The pulping conditions, exhibited in Table 1, were adjusted to obtain a pulp of kappa number 55 ± 2 in both species, this value is in line with industrial production in the "long fiber" segment. For each condition were performed four cooking repetitions.

Table 1. The Kraft pulping conditions.

Tabela 1. Condições da polpação Kraft.

Parameters	Conditions
Alkali charge (NaOH base), %*	24**, 29***
Sulfidity, %	25
Maximum temperature, °C	170
Liquor / wood ratio, L·kg ⁻¹	4
H factor	800
Dry mass of chips, g	150

* % on over dried wood chips; ** The Alkali charge to reach the target kappa number of *P. taeda*; *** The Alkali charge to reach the target kappa number of *C. japonica*.

The black liquor was collected in the end of the cooking, the residual active alkali (SCAN-N 2:28, 1988) and the total solids content (TAPPI T 650 om-15) (TAPPI, 2015b) were determined. The pulps were disaggregated, washed and screened in a laboratory scrubber of 0.5 mm slit. The screened yield, the kappa number and the selectivity for each pulp were determined according to Table 2.

Table 2. Determined parameters in the kraft pulping.

Tabela 2. Parâmetros determinados na polpação kraft.

Parameters	Standards / Procedures
Total yield	Ratio between the dry weight of cellulose and the dry weight of wood
Screened yield	Ratio between the dry weight of screened cellulose and the dry weight of wood
Rejects content	Ratio between the dry weight of rejects (material taken from the scrubber with 0.5 mm slit) and the dry weight of wood
Kappa number	TAPPI T 236 om-13 (TAPPI, 2013a)
Selectivity	Ratio between pulping screened yield and kappa number

The wood specific consumption, the consumed active alkali and the solid content created per ton in the produced pulp, were calculated according to equations 5, 6 and 7.

$$\text{WSC} = \frac{1}{\text{BDSY}} \quad (5)$$

Equation 5. WSC is the wood specific consumption ($\text{m}^3 \cdot \text{t}^{-1}$); BD is the basic density ($\text{g} \cdot \text{cm}^{-3}$); SY is the pulping screened yield in decimal.

$$\text{CAA} = \text{AAA} - \text{RAA} \quad (6)$$

Equation 6. CAA is the consumed active alkali ($\text{g} \cdot \text{L}^{-1}$); AAA is the applied active alkali ($\text{g} \cdot \text{L}^{-1}$); RAA is the residual active alkali ($\text{g} \cdot \text{L}^{-1}$).

$$\text{tss} \cdot \text{odt}^{-1} = \frac{(1 - \text{SY}) + \text{AAA}}{\text{SY}} \quad (7)$$

Equation 7. The $\text{tss} \cdot \text{odt}^{-1}$ is the solid content created per tonne of cellulose ($\text{t} \cdot \text{t}^{-1}$); SY is the pulping screened yield in decimal and AAA is the applied active alkali ($\text{g} \cdot \text{L}^{-1}$).

The pulp color was calculated with a Konica Minolta Spectrophotometer CM-5 connected to a computer adapted to a D65 light source and a 10° observation angle (CIE-Lab standard). The reflectance data were obtained with a spectral range from 400 to 750 nm. In five pulp samples, it was collected five spectra for each sample. A total of 25 spectra for each species were obtained.

The following color parameters were measured and calculated according to ASTM D2244-16 (ASTM, 2016): lightness (L^*), green-red coordinate (a^*), blue-yellow coordinate (b^*), color saturation (C^*), hue angle (h) as also the difference in the color between two kinds of produced pulps (ΔE).

Papermaking

The produced pulps were refined in a Jokro Mill (ISO 5267-3: 1979) (ISO, 2015b). It was used the equivalent of 16 dry grains, 6% consistency, pH 7 ± 0.5 , the temperature of 30°C and refining levels of 0, 3000, 6000 and 9000 revolutions.

After the refining process, handsheets weighing $60 \text{ g} \cdot \text{m}^{-2}$ were developed in the Rapid-Köethen papermaker (ISO 5269-2: 2004) (ISO, 2008). The leaves were kept in an air-conditioning environment with the temperature of $23^\circ\text{C} \pm 2^\circ\text{C}$ and $50\% \pm 2\%$ relative humidity (TAPPI T 402 sp-13) (TAPPI, 2013b). It was performed the test for physical-mechanical property and repeated it 10 times. The standards used for the tests are shown in Table 3.

Table 3. Standards of the physical-mechanical properties determined in the paper.

Tabela 3. Normas das propriedades físico-mecânicas determinadas no papel.

Parameters	Standards
Drainability	ISO 5267-1:1999 (ISO, 2015a)
Thickness	TAPPI T220 sp-16 (TAPPI, 2016c)
Specific volume	TAPPI T220 sp-16 (TAPPI, 2016c)
Apparent density	TAPPI T220 sp-16 (TAPPI, 2016c)
Air resistance of paper	TAPPI T460 om-16 (TAPPI, 2016d)
Tensile index	TAPPI T494 om-13 (TAPPI, 2013c)
Burst index	TAPPI/ANSI T403 om-15 (TAPPI, 2015c)
Tear index	TAPPI T414 om-12 (TAPPI, 2012)

Data analysis

For the wood characterization was made descriptive statistics (mean and coefficient of variation). For Kraft pulping and papermaking the tests of homogeneity and analysis of variance (ANOVA) were realized and when significant difference was detected between treatments the Tukey test was used, at 5% of significance.

The data were analyzed in the statistical software Statgraphics.

RESULTS AND DISCUSSION

Wood characterization

The results of the chemical characterization and the wood basic density of *C. japonica* and *P. taeda* are shown in Table 4.

Table 4. Characterization of *C. japonica* and *P. taeda* woods.

Tabela 4. Caracterização das madeiras de *C. japonica* e *P. taeda*.

Parameters	<i>C. japonica</i>	<i>P. taeda</i>
Wood basic density, $\text{g} \cdot \text{cm}^{-3}$	0.300 (1.89)	0.370 (1.78)
Extractives, %	0.81 (2.34)	2.46 (5.27)
Insoluble lignin, %	30.24 (2.03)	25.21 (1.70)
Soluble lignin, %	0.14 (2.44)	0.53 (4.00)
Total lignin, %	30.38 (1.36)	25.74 (1.74)
Holocellulose, %	68.81 (1.23)	71.80 (1.35)
Ash in wood, %	0.42 (3.52)	0.27 (2.02)

The first values are the means and the values in parentheses correspond to the coefficient of variation in percentage.

The *C. japonica* wood presented a lower basic density than the *P. taeda* wood. The result in the wood basic density of *C. japonica* indicates a higher wood specific consumption (MARON; NEVES, 2004), resulting in a negative economic impact (SARTO et al., 2015). However, there is not a significant correlation between the wood basic density and the pulping yield that would make possible the use of lower density wood for pulp production (GOMIDE et al., 2010).

The value of the wood basic density of *C. japonica* found in this study is higher than the one found by Carneiro et al. (2009) who studied 14-years-old trees, $0.25 \text{ g} \cdot \text{cm}^{-3}$. The value was also lower than the one found by Pereira et al. (2003) who studied 22-years-old-trees, $0.36 \text{ g} \cdot \text{cm}^{-3}$. The value of the wood basic density of *P. taeda* is between the range of 0.35 to $0.44 \text{ g} \cdot \text{cm}^{-3}$, which is commonly found for wood of *P. taeda* (RIGATTO et al., 2010).

The chemical composition of *C. japonica* presented higher ash content and total lignin as also lower extractives and holocellulose contents when compared to *P. taeda*. Lignin, extractive and ash in wood influence negatively the yield of the process, while a higher content of holocellulose benefits it (SMOOK, 2016).

Pereira et al. (2003) found different results in the chemical characterization of *C. japonica*: 4.90% of total extractives, 62.50% of holocellulose and 32.70% of total lignin. On the other hand, the results in the chemical characterization of *P. taeda* in the present study are very similar to the one found by Vivian et al. (2015): 2.83% of total extractives, 70.46% of holocellulose and 26.71% of total lignin.

The Table 5 shows the average values in the parameters related to the tracheids morphology in both species.

Table 5. Morphology of the tracheids of *C. japonica* and *P. taeda* woods.

Tabela 5. Morfologia dos traqueídes das madeiras de *C. japonica* e *P. taeda*.

Dimension/ Relation	<i>C. japonica</i>	<i>P. taeda</i>
Length, mm	2.38 (4.23)	3.75 (10.58)
Width, μm	25.06 (12.09)	49.43 (17.64)
Lumen diameter, μm	15.89 (24.67)	33.40 (23.51)
Wall thickness, μm	4.59 (26.55)	8.01 (34.78)
Wall fraction, %	37.54 (27.18)	32.61 (32.53)

The first values are the means and the values in parentheses correspond to the coefficient of variation in percentage.

The *C. japonica* tracheids presented less length, width, lumen diameter, wall thickness than the *P. taeda* tracheids. Generally, if the tracheids are lower in length, the lower is the paper strength (VIVIAN et al., 2015). The wall fraction in the tracheids of *C. japonica* is higher than *P. taeda*, according Shimoyama and Wiecheteck (1993). Tracheids with high wall fraction tend to be less flexible besides presenting a lesser degree of collapse in the paper making. It may interfere negatively in the interfiber bonds, reducing the tensile and the resistance to force as well as decreasing tear strength and apparent specific bulk.

The tracheids morphology resulted of *C. japonica* and *P. taeda* were similar to the results found by other authors. Pereira et al. (2003) demonstrated that *C. japonica* has tracheids with a 2.2 mm mean length, a width of $30.1 \mu\text{m}$, a lumen diameter of $19.2 \mu\text{m}$ and a wall thickness of $5.5 \mu\text{m}$. In the same species, Carneiro et al. (2009) found mean values for the tracheid: a length of 2.1 mm, a width of $29.4 \mu\text{m}$, a lumen diameter of $18.6 \mu\text{m}$ and a wall thickness of $5.3 \mu\text{m}$. Vivian et al. (2015) found mean values for the tracheid for *P. taeda*: a length of 3.5 mm, a width of $40.5 \mu\text{m}$, a lumen diameter of $27.7 \mu\text{m}$ and a wall thickness of $6.4 \mu\text{m}$.

Kraft pulping

The Table 6 shows the results of the pulping process for both species and the Table 7 shows the results of ANOVA, evaluating the performance of *C. japonica* and *P. taeda* in the kraft pulping process.

As planned, there was not statistical difference in the kappa number parameter ($F=0.0021 < F\text{-crit}=7.7086$). On the other hand, the statistical differences found in the total yield pulping ($F=11.8739 \geq F\text{-crit}=7.7086$), in the reject content ($F=64.5336 \geq F\text{-crit}=7.7086$) and in the screened yield ($F=21.7655 \geq F\text{-crit}=7.7086$), showed that the *C. japonica* species are superior in these parameters, despite of the statistical equal selectivity ($F=4.1667 < F\text{-crit}=7.7086$).

Table 6. Pulping process results.**Tabela 6.** Resultados do processo de polpação.

Parameter	<i>C. japonica</i>	<i>P. taeda</i>
Kappa number	53.85	53.80
Total yield, %	52.50	49.42
Rejects content, %	0.32	1.05
Screened yield, %	52.18	48.37
Selectivity	0.97	0.90
Wood specific consumption, m ³ ·t ⁻¹	6.45	5.59
Total solids generated, t·t ⁻¹	1.37	1.61
Total solids content, %	17.89	17.12
Residual active alkali, g·L ⁻¹	34.67	22.52
Consumed active alkali, g·L ⁻¹	8.83	13.48

Table 7. Basic statistical evaluation in the Kraft pulping performance from the studied woods.**Tabela 7.** Avaliação estatística básica do desempenho de polpação Kraft das madeiras estudadas.

Cause of variation	Degrees of freedom	Sum of squares	Mean square	Fisher's F-Test	P - value
Kappa number					
Between groups	1	0.0044	0.0044	0.0021	0.9650
Within groups	4	8.1287	2.0321		
Total	5	8.1331			
Total yield					
Between groups	1	14.2376	14.2376	11.8739	0.0261
Within groups	4	4.7962	1.1990		
Total	5	19.0339			
Rejects content					
Between groups	1	0.8003	0.8003	64.5336	0.0013
Within groups	4	0.0496	0.0124		
Total	5	0.8499			
Screened yield					
Between groups	1	21.7894	21.7894	21.7655	0.0095
Within groups	4	4.00439	1.0010		
Total	5	25.7938			
Selectivity					
Between groups	1	0.0073	0.0073	4.1667	0.1107
Within groups	4	0.0070	0.0017		
Total	5	0.0144			
Wood specific consumption					
Between groups	1	1.1130	1.1130	84.4881	0.0007
Within groups	4	0.0526	0.0131		
Total	5	1.1657			
Total solids generated					
Between groups	1	115.1521	115.1521	45.9568	0.0024
Within groups	4	10.0226	2.5056		
Total	5	125.1748			
Total solids content					
Between groups	1	0.8893	0.8893	78.4720	0.0008
Within groups	4	0.0453	0.0113		
Total	5	0.9346			
Residual active alkali					
Between groups	1	221,3317	221,3317	4608	0,00
Within groups	4	0,1921	0,0480		
Total	5	221,5238			
Consumed active alkaline					
Between groups	1	32.3947	32.3947	674.4392	1.31E-05
Within groups	4	0.1921	0.0480		
Total	5	32.5868			

The wood specific consumption of *C. japonica* was significantly higher than *P. taeda* ($F=84.4881 \geq F\text{-crit}=7.7086$). A higher wood specific consumption indicates that for the production of the same amount of pulp, a higher volume of wood will be required (SARTO et al., 2015).

Considering the higher screened yield, the *C. japonica* pulping developed significantly less solids per ton in the produced pulp ($F=45.9568 \geq F\text{-crit}=7.7086$), a black liquor with higher total of solids content ($F=78.4720 \geq F\text{-crit}=7.7086$) and a higher residual active alkali content ($F=4608 \geq F\text{-crit}=7.7086$). The higher development of solids may compromise the capacity of the production in the pulp mill, since the production decreases due to the fact of the fixed capacity of burning solids in the recovery boiler (VIVIAN et al., 2015).

The statistical difference found in the consumed active alkali ($F=674.4392 \geq F\text{-crit}=7.7086$) shows that, although a lower alkaline charge is necessary to reach the target kappa number, the pulping of *P. taeda* consumes more chemical reagents than the pulping of *C. japonica*.

The Table 8 shows the results of the color measurements of two kinds of pulp and the Table 9 shows the results of the evaluation of ANOVA in the colorimetric parameters of *C. japonica* and *P. taeda* pulps.

Table 8. Colorimetric parameters of *C. japonica* and *P. taeda* pulps.

Tabela 8. Parâmetros colorimétricos das polpas de *C. japonica* e *P. taeda*.

Species	L*	a*	b*	C*	h
<i>C. japonica</i>	66,26	5,76	17,13	18,07	1,25
<i>P. taeda</i>	66,03	5,73	19,13	19,97	1,28

L*: lightness; a*: green-red coordinate; b*: blue-yellow coordinate; C*: color saturation; h: hue angle.

Table 9. Basic statistical evaluation in the colorimetric parameters of *C. japonica* pulp and *P. taeda* pulp.

Tabela 9. Avaliação estatística básica nos parâmetros colorimétricos da polpa de *C. japonica* e da polpa de *P. taeda*.

Cause of Variation	Degrees of freedom	Sum of squares	Mean square	Fisher's F-Test	P - value
L*					
Between groups	1	0.4200	0.4200	1.8502	0.1846
Within groups	28	6.3572	0.2270		
Total	29	6.7773			
a*					
Between groups	1	0.0076	0.0076	0.5427	0.4674
Within groups	28	0.3961	0.0141		
Total	29	0.4038			
b*					
Between groups	1	30.0800	30.0800	349.4565	2.37E-17
Within groups	28	2.4101	0.0860		
Total	29	32.4902			
C*					
Between groups	1	301.7762	301.7762	2302.3630	1.96E-28
Within groups	28	3.6700	0.1310		
Total	29	305.4462			
h					
Between groups	1	0.0084	0.0084	361.8965	1.5E-17
Within groups	28	0.0006	2.32E-05		
Total	29	0.0090			

L*: lightness; a*: green-red coordinate; b*: blue-yellow coordinate; C*: color saturation; h: hue angle.

The results indicated that there was not significant difference in the lightness (L*) ($F=1.8502 < F\text{-crit}=4.1959$) and in the green-red coordinate (a*) ($F=0.5427 < F\text{-crit}=4.1959$). However, significant differences were found in the blue-yellow coordinate (b*) ($F=349.4565 \geq F\text{-crit}=7.7086$), in the color saturation (C*) ($F=2302.3630 \geq F\text{-crit}=4.1959$) and in the hue angle (h) ($F=361.8965 \geq F\text{-crit}=4.1959$). Therefore, the *P. taeda* pulp is more yellowish, saturated and with a higher hue angle than the *C. japonica* pulp.

The difference in the color between the two kinds of produced pulps (ΔE) was 2.01, considering it significant according to the classification proposed by Hikita et al. (2001).

Papermaking

The refining is a mechanical treatment when the pulp fibers are ruptured in fibrils to increase the fiber surface area (TEIXEIRA et al., 2017). The main purpose is to increase the capacity of interlacement among the fibers (SWINEHART, 2012). The refining effect in the physical-mechanical properties of *C. japonica* and *P. taeda* papers are shown in Table 9, Figure 1 and Figure 2.

Table 10. Average values of the physical-mechanical properties of *C. japonica* and *P. taeda* papers.

Tabela 10. Valores médios das propriedades físico-mecânicas dos papéis de *C. japonica* e *P. taeda*.

Parameter	Species	Refining level			
		0	3000	6000	9000
Drainability, °SR	C	14.00Da	15.66Ca	17.00Ba	20.00Aa
	P	11.33Cb	13.00Bb	13.00Bb	14.00Ab
Thickness, μm	C	145.10Ab	121.90Bb	117.60BCb	115.30Ca
	P	174.60Aa	130.70Ba	124.30Ca	118.30Da
Specific volume, $\text{cm}^3 \cdot \text{g}^{-1}$	C	2.23Ab	1.91Bb	1.89Bb	1.85Bb
	P	2.76Aa	2.10Ba	1.98Ca	1.91Ca
Apparent density, $\text{g} \cdot \text{cm}^{-3}$	C	0.45Ba	0.52Aa	0.53Aa	0.54Aa
	P	0.36Cb	0.47Bb	0.50Ab	0.52Ab
Air resistance of paper, s	C	4.40Ba	5.20Ba	6.10Aa	6.80Aa
	P	1.00Bb	1.20Bb	1.40Bb	2.00Ab
Tensile index, $\text{Nm} \cdot \text{g}^{-1}$	C	52.87Ba	69.97Aa	73.21Aa	75.59Aa
	P	50.10Aa	56.01Aa	58.77Ab	59.71Ab
Burst index, $\text{kPa} \cdot \text{m}^2 \cdot \text{g}^{-1}$	C	4.78Ba	7.24Aa	7.33Aa	7.40Aa
	P	2.75Cb	4.85Bb	5.18ABb	5.48Ab
Tear index, $\text{mNm}^2 \cdot \text{g}^{-1}$	C	133.87Aa	138.93Aa	141.37Aa	131.25Aa
	P	124.06Bb	146.86Aa	150.04Aa	142.25Aa

C: *C. japonica*; P: *P. taeda*. Different letters indicate a significant difference in the Tuley test at 5% of probability; capital letters refer to differences between refining levels and lowercase letters refer to differences between the studied species.

Figure 1. Drainability (A), Thickness (B), Specific Volume (C), Apparent Density (D).

Figura 1. Drenabilidade (A), Espessura (B), Volume Específico (C), Densidade Aparente (D).

The drainability is used to determine the intensity of the refining. It measures the resistance of drainage in a fibrous suspension (ROBUSTI et al., 2014). In the present study, the drainability in both types of pulps increased significantly. However, the drainability of the *C. japonica* pulp was higher, indicating that to reach a certain °SR, the *C. japonica* pulp will always consume less energy in the refining than the *P. taeda* pulp (Figure 1A).

When the intensity of the refining is higher, the thickness of the paper hand sheet is lower and the tendency of cellulosic fibers to collapse is also bigger (ROBUSTI et al., 2014). In the study of both species, the refining had significant influence in the thickness reduction. The paper hand sheets made from the pulp of *C. japonica* had a smaller thickness reduction when the refining is less intense, equalizing to the thickness of the paper made of *P. taeda* pulp in the most intense level of refining (9000 revolutions). It indicates that smaller levels of refining are sufficient to promote a collapse in the *C. japonica* fibers (Figure 1B).

Specific volume is the relation of volume per mass and the apparent density is the relation of mass per volume (TAPPI, 2016c). Influenced by the thickness, the first one tends to decrease with the refining and the second one, to increase (ROBUSTI et al., 2014). In the present study this tendency was identified, however, the papers made of *C. japonica* pulp always present a lower volume and a higher apparent density (Figure 1C and 1D).

The air resistance measures the time that a certain volume of air goes through the paper (TAPPI, 2016d) and connected to the refining treatment. When the refining level is bigger, the resistance to air is also bigger (ROBUSTI et al., 2014). The papers made of *C. japonica* pulp always presented significantly greater air resistance besides arriving at the top with a lower level of refining than the papers made of *P. taeda* pulp (Figure 2A).

The tensile index is the maximum force that the paper supports before breaking (TAPPI, 2013c; ROBUSTI et al., 2014). In the present study, the papers made of *C. japonica* pulp without the refining treatment, presented a lower tensile index than the refined ones, which in turn were not statistically different among themselves, the refining had no significant effect on the traction index of the papers formed with *P. taeda* pulp (Figure 2B). Considering the comparison between the species, only the papers made of high refined *C. japonica* pulps (6000 and 9000 revolutions) presented values statistically higher than the papers formed with *P. taeda* pulps.

Figure 2. Air Resistance of the paper (A), Tensile Index (B), Burst Index (C), Tear Index (D).

Figura 2. Permeância ao ar (A), Índice de Tração (B), Índice de Arrebentamento (C), Índice de Rasgo (D).

The burst index measures the maximum hydraulic pressure that the paper can resist until it ruptures (ROBUSTI et al., 2014; TAPPI, 2015c). In the present study, followed by the tensile index, the papers made of *C. japonica* pulp without the refining treatment, presented a lower burst index than the refined ones. There were not statistically differences between them (Figure 2C). For the papers made of *P. taeda* pulps, the refining treatment significantly increased the burst index, but did not make these values bigger than the burst index of the *C. japonica* papers.

The tear index measures the work necessary to complete the tearing of paper (SAMISTRARO, et al., 2009; TAPPI, 2012). This index is influenced by several factors, among them are highlighted length, thickness, stiffness and orientation of the fibers, as well as the refining degree (ROBUSTI et al., 2014). The tear index of the papers made of *C. japonica* pulp did not suffer significant effect in the refining treatment. In the paper made of *P. taeda* pulp, the absence of refining treatment promoted a significantly lower value (Figure 2D).

CONCLUSIONS

The *C. japonica* wood presented lower basic density, lower extractive content, higher total lignin content, higher ash content and lower holocellulose content than the *P. taeda* wood. The dimensions of *C. japonica* fibers were much smaller than *P. taeda* fibers.

The kraft pulpin of *C. Japonica* presented better yields, lower reject content, lower active alkali consumption and less solids per ton of produced pulp than the kraft pulping of *P. taeda*. However, it required a higher alkaline charge to reach the target kappa number and there was a higher wood specific consumption than *P. taeda*.

The papers made of *C. japonica* pulp had better physico-mechanical properties than the papers made of *P. taeda* pulp, emphasising the drainability, the air permeance, the tensile index and the burst index. The reason for this is the better response of *C. japonica* pulp to the refining process.

The present study demonstrated that *C. japonica* wood is very suitable for kraft pulping and papermaking for the "long fiber" segment.

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