

Bamboo kraft pulping

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Abstract

Despite of the wide use worldwide, the industrial potential of bamboo species in Brazil is not much investigated. However, some encouragement to revert this situation was created in last few years. The aim of this research was to evaluate the technological characteristics of the *Bambusa vulgaris* biomass for the production of pulp by the kraft process. The technological characteristics of the raw material were determined by the basic density, the chemical composition and the morphology of the fibers. The cooking process was carried out with the application of eight charges of active alkali, in 90 minutes of heating time and 60 minutes in the maximum temperature of 170°C. All analyzes were also executed with the *Eucalyptus* spp. and the *Pinus* spp., in order to make a complete comparison among the species *Bambusa vulgaris* and the two most used raw materials for the pulp production in Brazil. The *Bambusa vulgaris* presented a higher basic density, lower holocellulose content and a higher total extractive content. Its fibers have intermediate length and wall thickness, similar to the *Eucalyptus* spp. and the *Pinus* spp. Considering the kraft pulping process, the species *Bambusa vulgaris* demonstrated to be easier to delignify besides presenting almost zero reject content and smaller consumption of active alkali. However, the *Eucalyptus* spp. and the *Pinus* spp. obtained the best yields, the lowest specific consumption of raw material and better selectivities.

Keywords: Pulp, Paper, Non-wood products, *Bambusa vulgaris*.

Introduction

Brazil is now the world's second largest producer of pulp and the eighth in paper production, with a production of 19.5 million tons of pulp and 10.5 million tons of paper in 2017 (IBÁ 2018). Despite of presenting a wide diversity of species in native forest, the Brazilian pulp and paper industries are based on the use of only two exotic genera: *Eucalyptus* spp. and *Pinus* spp. The search for new raw materials for pulp production may contribute in terms of demand for specific types of pulp and the possibility of expansion in appropriated regions to produce planted forests (Sarto et al. 2015).

Bamboo is a rapidly grown agricultural crop from the family of grasses (Bhardwaj 2019), in the world 1,439 species of bamboos were catalogued, distributed in 116 genera (BPG 2012) and more than four thousand utilities (Pereira and Beraldo, 2016), two of them are the production of pulp and paper, especially on the Asian continent (Yang et al. 2008; Batalha et al. 2012; Borges et al. 2018; Bhardwaj 2019). Bamboo species are considered ideal crops for the rural development in developing countries (Brant et al. 2019), in Brazil, the cost of wood is increasing, mainly due to the high price of land (Batalha et al. 2012), so the replacement of wood by a fast-growing and short cutting cycle crop, such as

bamboo, can cheapen the price of several forest products, such as cellulose and paper.

The recognition of the great industrial potential of bamboos was not sufficient to create a considerable use of these species in Brazil, especially due to the lack of technical knowledge about them. In order to change this situation and stimulate the study, the cultivation and the use of bamboos in Brazil, the National Policy for the Incentive of Bamboo Management and Cultivation was established in 2011 (Do Vale et al. 2017; Sette Junior, 2017; Brant et al. 2019), instituted by Law number 12,484 /2011 (Brasil 2011).

Unlike Brazil, China takes full advantage of the industrial potential of bamboo species, being the country with the largest planted area, the largest processed volume and the largest number of bamboo products (Wang et al. 2019). China has a long tradition for using non-wood raw materials for pulp and paper due to its limited forest resources (Hammett et al. 2001), in that country bamboo is the main source of raw material for pulp and paper (Hammett et al. 2001).

For pulp and paper production the knowledge of technological characteristics of the raw-material, such as basic density, chemical composition and fiber morphology and its connection with the pulping results are very important for the determination of the wood quality as well as its adequate application (Vivian et al., 2015).

Considering it all, the present study intended to analyze the potential of the *Bambusa vulgaris* Schrad. ex J.C.Wendl biomass in the Kraft pulping process besides a comparison between the two most used wood for this purpose in Brazil, the *Pinus* spp. and the *Eucalyptus* spp, for this a complete analysis of the raw materials technological characteristics and their behavior in the kraft pulping processes were carried out.

Material and Methods

To conduct the present study, it was used industrial biomass chips of the *Bambusa vulgaris* from the city of Coelho Neto, Maranhão state, Brazil, 4°15'25" S 43°0'46" W WSG84 coordinates and industrial wood chips of the *Pinus* spp. and the *Eucalyptus* spp. from the city of Telêmaco Borba, Paraná state, Brazil, 24°19'26" S 50°36'57" W WSG84 coordinates.

The wood chips were submitted to a thickness control between 4 and 6 mm. These different values prevent the circulation of the chemical reagents as also the impregnation in the pulping process (Kocurek 1992).

The parameters determined in the raw materials were the basic density (TAPPI 2016b); the fiber dimensions, considering length, width and lumen diameter parameters (IAWA 1989); the total extractives content (TAPPI 2017); the insoluble lignin content (TAPPI 2015a); the soluble lignin content (Goldschimid 1971) and the wood ash (TAPPI 2016a).

The wall thickness, the wall fraction, the total lignin content and the holocellulose content were calculated according to equations (1) to (4).

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

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

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

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

WT is the wall thickness (μm), FW is the fiber width (μm), LD is the lumen diameter (μm), WF is the wall fraction (%), LT is the total lignin content (%), IL is the insoluble lignin content (%), SL is the soluble lignin content (%), Holo

is the holocellulose content (%) and TE is the total extractive content (%).

About dimensions, one hundred fibers of each raw material were measured; the basic density and the chemical characterization for each raw material were performed in five replicates.

The Kraft cooking was carried out in a rotating autoclave containing individual stainless-steel capsules with a capacity of 450 mL each. The analyses were performed in three replicates according to the process conditions in Table 1.

Table 1. The conditions in the Kraft pulping process.

Parameters	Conditions
AAA*	10, 12, 14, 16, 18, 20, 22 and 24
Sulfidity**	25
Maximum temperature ($^{\circ}\text{C}$)	170
Heating time (minutes)	90
Cooking time (minutes)	60
Liquor-to-biomass ratio ($\text{L} \cdot \text{kg}^{-1}$)	4
H factor	1100
Dry mass of chips (g)	70

* Percentage of active alkali active applied on over dried biomass in NaOH base. **Percent of Na_2S in the active alkali.

After cooking, the black liquor was collected to determine the residual active alkali (SCAN, 1988) and the total solids content (TAPPI 2015b). The pulps were disaggregated, washed and screened in a laboratory scrubber with a 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 process.

Parameters	Standards / Procedures
Pulping total yield	Ratio between the dry weight of pulp and the dry weight of wood
Pulping screened yield	Ratio between the dry weight of screened pulp 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 2013)
Selectivity	Ratio between pulping screened yield and kappa number

The consumption of the specific raw material, the active alkali and the solid content created per ton of produced pulp were calculated according to equations (5) to (7).

$$SRC = \frac{1}{BD \cdot SY} \quad (5)$$

$$CAA = AAA - RAA \quad (6)$$

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

SRC is the specific raw material consumption ($\text{m}^3 \cdot \text{t}^{-1}$), BD is the basic density ($\text{g} \cdot \text{cm}^{-3}$), SY is the pulp-ing screened yield in decimal, 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 ($\text{g} \cdot \text{L}^{-1}$) and $tss \cdot odt^{-1}$ is the solid content generated per tonne of pulp ($\text{t} \cdot \text{t}^{-1}$).

Results and discussion

The results of the chemical characterization and the basic density of the raw materials are shown in Table 3.

The *Pinus* spp. and the *Eucalyptus* spp. presented close values in the basic densities, but inferior to the basic density of the *Bambusa vulgaris*. The literature demonstrated values of the basic density for species cultivated in Brazil. It alternates from 0.46 to 0.51 $\text{g} \cdot \text{cm}^{-3}$ for *Bambusa vulgaris* biomass (Andrade et al. 2015), from 0.35 to 0.44 $\text{g} \cdot \text{cm}^{-3}$ for wood of the genus *Pinus* spp. (Rigato et al. 2004) and from 0.36 to 0.54 $\text{g} \cdot \text{cm}^{-3}$ for wood of the genus *Eucalyptus* spp. (Mokfienski et al. 2008). The *Eucalyptus* spp. wood which was used in the current study presented lower values of basic density, that is usually found in fast-growing planted forest, but low wood basic density is undesirable for pulp production because of its negative impact on pulp throughput (tons of pulp per hectare of land) (Vidaurre et al. 2018) and high specific raw material consumption.

Table 3. Physical and chemical characterization of the studies raw materials.

Parameters	<i>Bambusa vulgaris</i>	<i>Pinus</i> spp.	<i>Eucalyptus</i> spp.
Basic density ($\text{g} \cdot \text{cm}^{-3}$)	0.49 (0.73)	0.37 (1.78)	0.38 (2.37)
Total extractives (%)	11.55 (3.90)	2.46 (5.27)	2.40 (2.04)
Insoluble lignin (%)	21.29 (0.89)	25.21 (1.70)	22.69 (4.66)
Soluble lignin (%)	0.88 (4.55)	1.17 (2.96)	5.30 (2.96)
Total lignin (%)	22.17 (0.90)	26.39 (1.74)	27.99 (4.17)
Holocellulose (%)	66.28 (0.77)	71.16 (1.35)	69.61 (1.38)
Wood ash (%)	1.10 (6.36)	0.27 (2.02)	0.36 (4.72)

The values in parentheses correspond to the variant coefficients in percentage.

In the chemical composition, the *Bambusa vulgaris* presented a higher extractive content, a lower total lignin and holocellulose content than the *Pinus* spp. and the *Eucalyptus* spp. The lignin, the extractive and the wood ash influenced negatively the process of the yield (Smook 2016). Although it presented a lower total lignin, the high contents of

extractives and ash, the lower holocellulose content, put the *Bambusa vulgaris* biomass in disadvantage between the other two raw materials studied.

The table 4 presents the results of the parameters related to the fiber morphology.

Table 4. Fiber dimensions and its relation.

Dimension/Connections	<i>Bambusa vulgaris</i>	<i>Pinus</i> spp.	<i>Eucalyptus</i> spp.
Length (mm)	2.58 (16.36)	3.75 (10.58)	1.13 (7.47)
Width (µm)	20.13 (21.76)	49.43 (17.67)	18.48 (13.99)
Lumen diameter (µm)	10.19 (29.76)	33.40 (23.51)	11.30 (26.40)
Wall thickness (µm)	5.30 (37.20)	8.01 (34.78)	3.59 (22.51)
Wall fraction (%)	49.38 (24.58)	32.61 (32.53)	39.48 (23.14)

The values in parentheses correspond to the variant coefficients in percentage.

The pulp originated from softwoods, the species of the genus *Pinus*, is called long fiber pulp, with the fibrous structure between 2 and 5 mm length. There is an application in the paper that demands greater resistance, like the case of the paper used in the manufacture of packaging. On the other hand, the pulp originated from hardwoods, the species of the genus *Eucalyptus* with short fiber pulp which may vary from 0.5 to 2 mm, is used for the production of printing and writing papers as well as the tissue paper for sanitary purposes.

The pulps from raw material with smaller wall thickness are ideal for the production of printing and writing paper and the pulps from raw material with bigger wall thickness are ideal for absorbent paper, because of the bigger potential of liquid absorption (Santos and Sansígolo, 2007; Mokfienski et al. 2008). The literature demonstrated values of fiber length and wall thickness similar that was found in this research, 2.38 mm and 5.95 µm for *Bambusa vulgaris* (Borges et al. 2018), 3.50 mm and 6.41 µm for *Pinus taeda* (Vivian et al. 2015) and 1.04 mm and 3.71 µm for the hybrid of *Eucalyptus grandis* x *Eucalyptus urophylla* (Sarto et al. 2015), all of them cultivate in Brazil for pulp and paper production.

The results presented that the species *Bambusa vulgaris* obtain intermediate values of fiber length and wall thickness in relation to the *Pinus* spp. and the *Eucalyptus* spp. It may be used to produce long fiber pulp and short fiber pulp simultaneously, the second option is more suitable for absorbent papers. On the other hand, *Bambusa vulgaris* obtain a higher wall fraction in a parameter directly related to a higher basic density (Sarto et al. 2015; Paulino and Lima 2018), it represents more rigid fibers, which results in lower tensile and rupture strengths besides higher specific volumes and tear strength in the paper.

It is possible to observe in the Figure 1, the results of the pulping process of the studies raw materials.

The *Bambusa vulgaris* biomass presented screened yields much lower than the other two raw materials studied with 12% of the active alkaline applied (Figure 1B). In addition, the specific consumption of the *Bambusa vulgaris* demonstrated a strong growth, while with the other studied raw materials, this parameter showed a stable trend (Figure 1E).

The specific consumption is based on the pulping yields and the basic density. This is an important parameter for pulp mills and it reveals the necessity of the wood volume to achieve a certain production rate of the pulp (Segura and Silva

Júnior 2016). In a pulp mill, the wood represents the highest cost in production. Therefore, higher yields and lower specific consumption imply in a reduction of the cost. In the present study, the basic density was not a determinant factor in the differences of the specific consumption between the species, it was directly influenced by the screened yield.

The biomass of the *Bambusa vulgaris* presented a considerable facility of delignification if compared to the woods of the *Pinus* spp and the *Eucalyptus* spp. Its minimum kappa number was 8.8 while minimum kappa numbers for the *Pinus* spp. and the *Eucalyptus* spp. were respectively, 31.2 and 12.8. In the present study, the results demonstrated that if the total lignin content is lower, the easier is to delignify.

The species *Bambusa vulgaris* presents a lower screened yield for any kappa number range (Figure 1F). As previously mentioned, this fact is explained by the high extractive and ash contents presented in the species, causing pulp yield decrease (Smook 2016).

The active alkali consumed, the black liquor solids content, the selectivity and the generated solids in the pulping process are presented in the Figure 2.

The selectivity in the pulping process may be indicated by the ratio between the screened yield and the kappa number of the pulp (Vivian et al. 2015). If the kappa number is less than 30, it is only possible to compare the selectivity between the *Bambusa vulgaris* biomass and the *Eucalyptus* spp. wood, being the lowest selectivity for the pulping of *Bambusa vulgaris*. If the kappa number is between 30 and 80, there are selective values for all the raw materials studied. Again, the lowest selectivity is for the *Bambusa vulgaris* pulping (Figure 2A). It represents that any delignification range the pulping yields of the *Bambusa vulgaris* biomass will always be lower than the yields for wood pulping of the *Pinus* spp. and the *Eucalyptus* spp.

For the same range of delignification, the pulping of *Bambusa vulgaris* biomass is the one that consumes less active alkali (Figure 2B) and the one that produces black liquor with lower solids content (Figure 2C). On the other hand, it produces the highest amount of solids per ton of produced pulp (Figure 2D). There is a fixed solid-burning capacity in the recovery boiler, a raw material that provides many solids per ton in a produced pulp, compromises the pulp mil production capacity (Vivian et al. 2015).

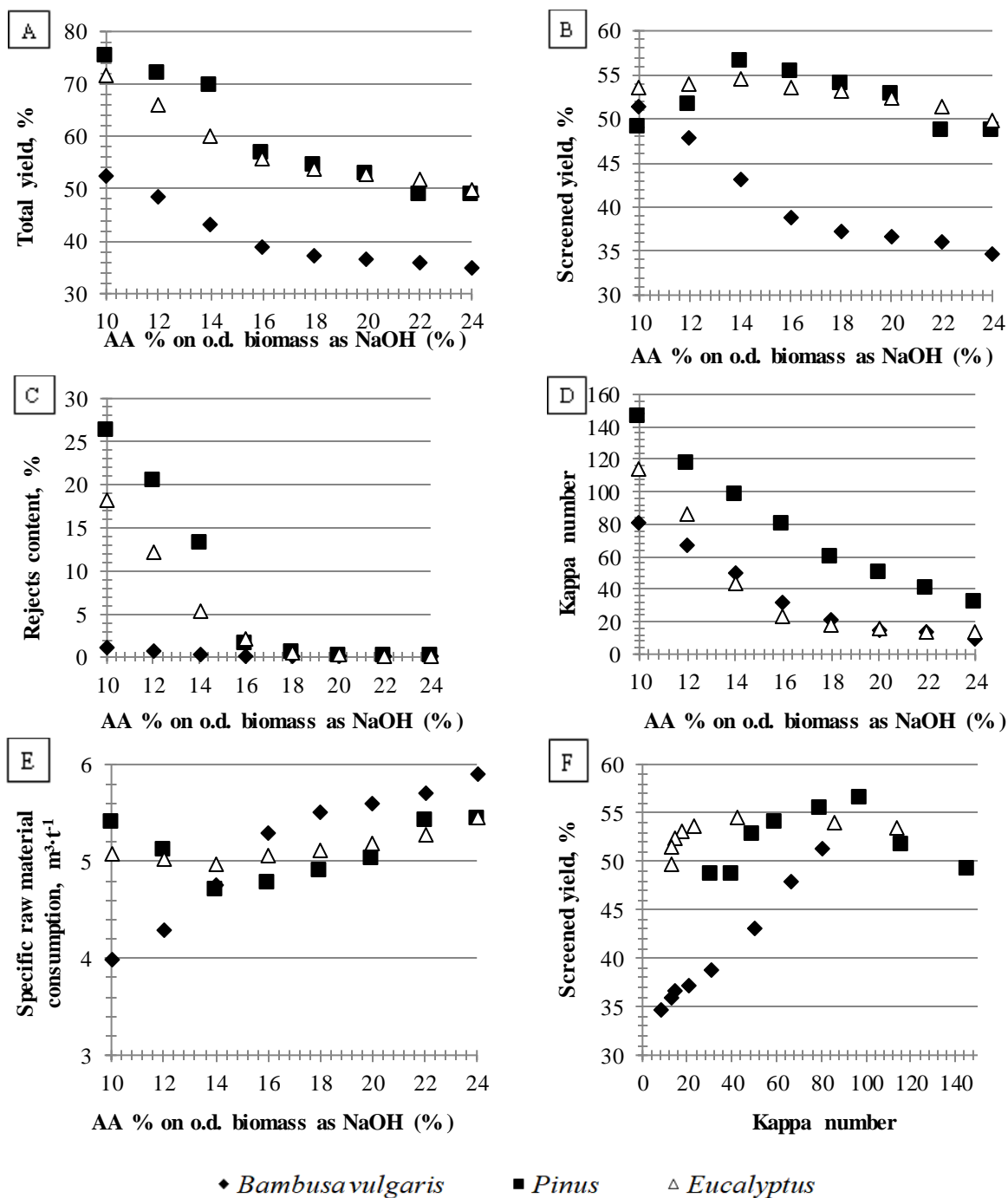


Figure 1. Total yield (A), Screened yield (B), Rejects content (C), Kappa number (D), Biomass specific consumption (E) and the connection between screened yield and kappa number (F).

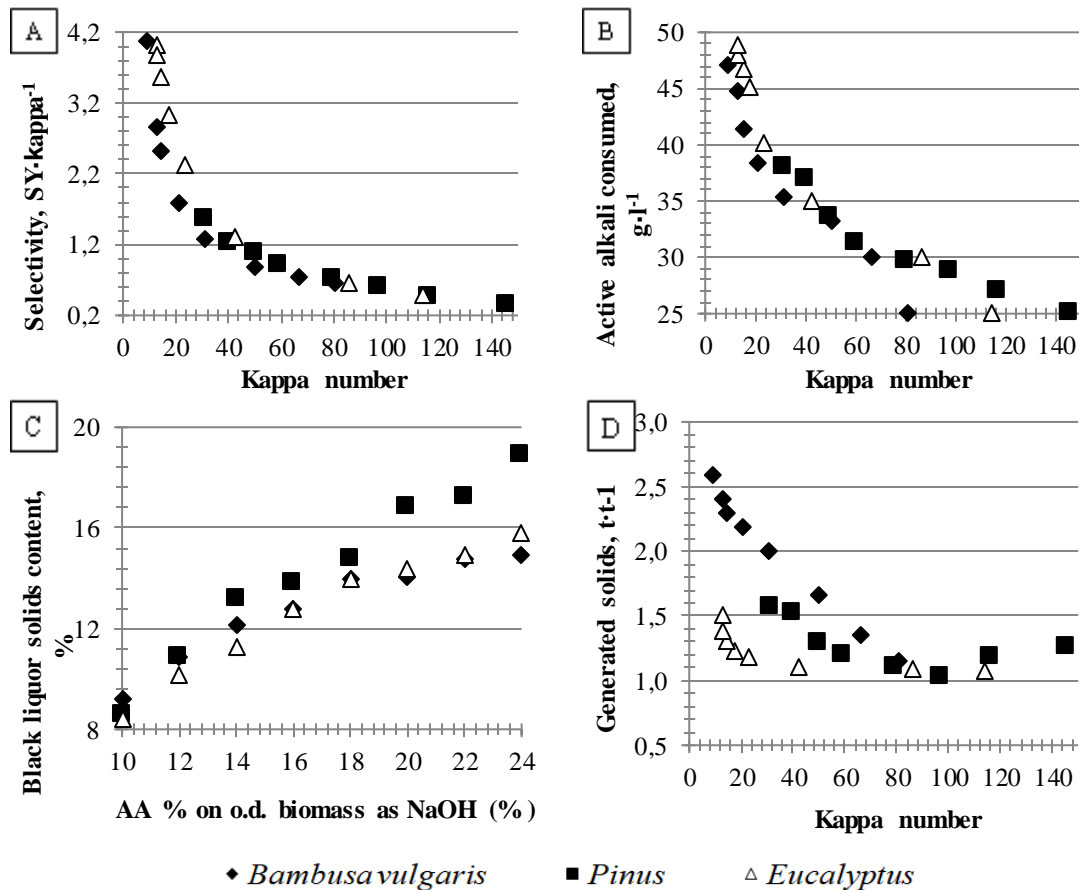


Figure 2. Selectivity (A), Active alkali consumed (B), Black liquor solids content (C) and the generated solids in the pulping process (D).

Conclusions

The biomass of the *Bambusa vulgaris* presented a higher basic density than the *Pinus* spp. and the *Eucalyptus* spp. For the production of pulp, the chemical characteristics of the *Eucalyptus* spp. and the *Pinus* spp. are superior to the *Bambusa vulgaris*, because there is a higher content of holocellulose with lower contents of extratives and ash on *Bambusa vulgaris*.

The fibers of *Bambusa vulgaris* presented an intermediate length and wall thickness in relation to the *Eucalyptus* spp. and the *Pinus* spp., being suitable for the production of paper for packaging or absorbent purposes.

Comparing the performance of the studied raw materials in the pulping process, the species *Bambusa vulgaris* demonstrated a lower content of rejects, a bigger facility of delignification and, consequently, a lower consumption of active alkali. On the other hand, it presented lower yields, lower selectivity and higher solids content per ton of produced pulp than the *Eucalyptus* spp. and the *Pinus* spp.

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