ASSESSMENT OF INDUSTRIAL PERFORMANCE FOR MARKET PULP PRODUCTION BETWEEN EUCALYPT AND *Corymbia* HYBRIDS CLONES

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ABSTRACT – The search for novel biomasses for uses as alternative fiber sources, similar to *Eucalyptus* spp. biomass, holds great value and potential for commercial-scale application. This study aims to present the hybrid clones of *Corymbia* spp. developed by Aperam BioEnergia as potential substitutes for *Eucalyptus* wood in the market pulp industry. By performing modified kraft pulping and chemical characterization analyses, it was possible to compare the biomass of *Eucalyptus* spp. with that of *Corymbia* spp. Comparisons were made by analyzing their respective pulp average growth rate (PAGR) and specific wood consumption (SWC), estimated using a kappa number of 19 ± 1. The results showed that one of the hybrid clones (*Corymbia citriodora* × *Corymbia torelliana* - ID 4) had highest PAGR#k19, and lowest SWC than other samples. Clone ID 4 showed lowest value of SWC since, simultaneously presented a higher value of wood basic density and screened yield. Consequently, in agreement with its best results, clone ID 4 had the highest-ranking score, calculated as the PAGR/SWC ratio. This genetic material also showed one of the lowest total lignin content, consequently the highest screening yield. Besides Clone ID 4 showed significantly highest xylan content, among wood samples assessed in this work. For that reason, the ID 4 was the highest-ranked, proving to be an excellent high-performance alternative for forest-industry interface parameters.

Keywords: *Eucalyptus* vs *Corymbia*; Modified kraft pulping; PAGR.

AVALIAÇÃO COMPARATIVA DO DESEMPENHO INDUSTRIAL PARA PRODUÇÃO DE POLPA CELULÓSICA ENTRE EUCALIPTO E HÍBRIDOS DE Corymbia

RESUMO –A busca por biomassas para uso como fontes alternativas de fibras, semelhantes a biomassa de ***Eucalyptus*** *spp., possui grande valor e potencial para aplicação em escala comercial. Este trabalho tem como objetivo apresentar os clones híbridos de* ***Corymbia*** *spp. desenvolvidos pela Aperam BioEnergia como potenciais substitutos da madeira de eucalipto na indústria de polpa celulósica. Ao realizar a polpação kraft modificada e análises de caracterização química, foi possível comparar a biomassa de* ***Eucalyptus*** *spp. com a de* ***Corymbia*** *spp. As comparações foram feitas analisando o incremento médio anual de celulose (IMACel) e consumo especifico de madeira (CEMad), estimados usando um número kappa de 19 ± 1. Os resultados mostraram que um dos clones híbridos (****Corymbia citriodora*** *×* ***Corymbia torelliana*** *- ID 4) apresentou maior densidade básica, maior rendimento depurado, melhor IMACel#k19 e menor CEMad do que as outras amostras. O clone ID 4 demonstrou menor valor de CEMad pois, simultaneamente, apresentou maior valor de densidade básica e rendimento depurado. Consequentemente, de acordo com seus melhores resultados, o clone ID 4 obteve a pontuação mais alta, calculada pela razão IMACEL/CEMad. Este material genético também*

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apresentou um dos menores teores de lignina total, resultando em um maior rendimento depurado. Além disso, o clone ID 4 apresentou teor de xilana significativamente maior dentre as amostras de madeira avaliadas neste trabalho. Dessa forma, o ID 4, foi o mais bem classificado, provando ser uma excelente alternativa de alto desempenho para parâmetros de interface floresta-indústria

Palavras-Chave: ***Eucalyptus*** *vs* ***Corymbia****; Polpação kraft modificada; IMACel.*

1. INTRODUCTION

The Brazilian pulp sector has aimed to significantly increase its production scale. The country stands out as the largest exporter of pulp to the global market, with a trade balance of US$ 6,0 billion, produced mainly from *Eucalyptus* spp. (IBÁ, 2021). In the country, short-fiber pulp is used for the production of different types of paper (printing and writing, tissue, and packaging), with an annual export volume of 15 million air dry tonnes (ADt). Therefore, there is considerable demand for wood with operating costs equal to or lower than that of *Eucalyptus* spp., as well as with equal or superior quality, to be used as a fibrous source in Brazil (Sanquetta, 2020).

As *Eucalyptus*, the genus *Corymbia* belongs to the Myrtaceae family and has a total of 113 species, which are naturally distributed along the east coast of Australia (Tambarussi et al., 2018). Until the 1990s, the species of these genera were classified as *Eucalyptus*. However, due to genetic divergences, *Corymbia* was officially considered a new genus by the scientific community (Hill and Johnson, 1995).

Wood from *Corymbia* spp. hybrid clones have been little explored in the pulp and paper industry. According to Loureiro et al. (2019), interspecific *Corymbia* hybrids tend to have high biomass production, high density, and rapid growth. Furthermore, these materials are tolerant to biotic and abiotic stresses, such as wind, water deficit, frost, and most pests and diseases that cause economic damage to planted forests (Nahrung et al., 2010). It is believed that such superiority is due to heterosis, or hybrid vigor, an important phenomenon for improving forest productivity, as it allows the combination of alleles of interest from different species (Goulet et al., 2017).

Despite the high performance of *Corymbia* clones, the forest sector still has strong restrictions and concerns regarding the use of this material (Reis et al., 2014). Therefore, it is necessary to study and develop new technologies and processes for this genus. Parameters such as pulp average growth rate (PAGR, ADt ha^{-1} $year^{-1}$), which relates to forest productivity (Foelkel, 2017), and specific wood consumption (SWC, m^3 ADt^{-1}), which contributes to predicting operating costs (Gallo et al., 2018), are important for material assessment. With these data, it is possible to rank commercial clones on the basis of their pulp production capacity per unit of planted area throughout the planting period.

In recent decades, environmental pressures and the need to increase pulp delignification to improve process efficiency and pulp quality have stimulated the development of new pulping technologies, including modified cooking methods (Segura, 2012). Modified kraft pulping can be used to produce pulp from *Corymbia* spp. and increase the selectivity of pulping processes for high density woods. This method provides adequate wood chips impregnation with division of the alkali charge, preventing carbohydrate degradation (Da Silva et al., 2016).

Modified kraft pulping allows for a better distribution of the alkali charge, thereby avoiding intense chemical activity at the beginning and end of the procedure (Santos et al., 2015). Thus, some of the advantages of the method include good impregnation of wood chips before delignification, uniformity and reduced cooking temperatures in the digester, reduced active alkali consumption, increased screened yield, low reject generation, and enhanced pulp quality and bleaching (Segura et al., 2016; Gomes, 2009; Bassa, 2006).

Given the above, this study aimed to develop technological alternatives for mitigating the major bottlenecks associated with the use of *Corymbia* spp. hybrid clones with high basic wood density. We also aimed to rank commercial clones of *Eucalyptus* spp. and hybrids of *Corymbia* spp. on the basis of indicative parameters for forest yield (PAGR and SWC) using an industrial modified kraft pulping protocol and chemical characterization.

2. MATERIAL AND METHODS

We analyzed 16 wood chips samples from trees aged 6.5 years, obtained from the industrial unit of Aperam BioEnergia, Vale do Jequitinhonha, Minas Gerais State, Brazil. Samples were identified according to the genetic stock (Table 1).

2.1. Modified kraft pulping

Pulping was performed in an MK digester (model 610-2), which comprises two reactors with a capacity of 7 L and an electronic control unit connected to a computer. An aliquot of 400 g of dry wood chips was placed in the MK digester and heated electrically. Temperature data were monitored at 1-min intervals during pulping, allowing determination of temperature and H-factor profiles.

The effective alkali charge (EA, %), determined as NaOH consumption on a dry wood basis, was selected after the exploratory tests, aiming at a kappa number of 19 ± 1. Modified kraft pulping was performed according to the following steps: (1) Wood chips were pre-vaporized under low-pressure steam (3.5 bar) for 15 min, whereby the wood chips surface temperature was increased to about 105 °C; (2) Wood chips were impregnated by adding 55% of the total EA, followed by increasing the temperature from 105 to 135 °C (15 min ramp) and maintaining at 135 °C for 90 min; (3) Cooking was achieved by draining the impregnation liquor followed by injection of the white liquor, reaching 45% of the total EA; the temperature was increased from 135 to 165 °C in 10 min and maintained at 165 °C for 90 min with a liquor/wood ratio of 4:1; and (4) Washing was carried out at the end of the process, and black liquor was extracted by displacement. The washing process was carried out in two phases. The first consisted of an alkaline wash at 3% EA followed by extraction. During the first phase, the temperature was reduced to 90 °C and held for 60 min. In the second phase, hot water (90 °C, 9 m^3 ADt^{-1}) was applied for 15 min and the temperature was reduced to 40 °C.

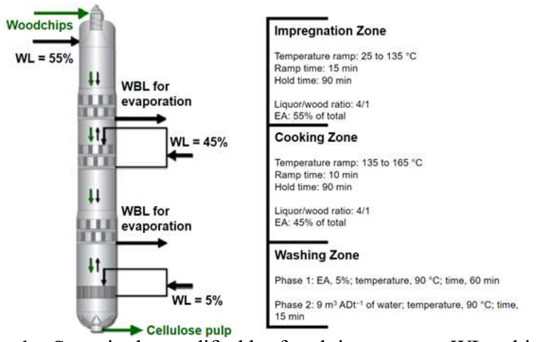

Figure 1 – Steps in the modified kraft pulping process. WL, white liquor; WBL, weak black liquor; EA, effective alkali.
Figura 1 – *Etapas do processo de polpação kraft modificada. Licor branco (WL); licor negro fraco (WBL); álcali efetivo (EA).*

Table 1 – Genetic stocks used for lab-scale evaluation of wood and pulp properties.
Tabela 1 – *Materiais genéticos utilizados para avaliação em escala laboratorial das propriedades da madeira e da polpa celulósica.*

ID	Genetic stock (6.5 years of age)
1	*Corymbia citriodora* × *Corymbia torelliana*
2	*Corymbia citriodora* × *Corymbia torelliana*
3	*Corymbia citriodora* × *Corymbia torelliana*
4	*Corymbia citriodora* × *Corymbia torelliana*
5	*Eucalyptus cloeziana*
6	*Eucalyptus urophylla* × *Eucalyptus* spp.
7	*Eucalyptus urophylla* × *Eucalyptus* spp.
8	*Eucalyptus urophylla* × *Eucalyptus* spp.
9	*Eucalyptus grandis* × *Eucalyptus urophylla*
10	*Eucalyptus urophylla* × *(Eucalyptus camaldulensis* × *Eucalyptus grandis)*
11	*(Eucalyptus camaldulensis* × *Eucalyptus grandis)* × *Eucalyptus urophylla*
12	*(Eucalyptus camaldulensis* × *Eucalyptus grandis)* × *Eucalyptus urophylla*
13	*(Eucalyptus camaldulensis* × *Eucalyptus grandis)* × *Eucalyptus urophylla*
14	*(Eucalyptus camaldulensis* × *Eucalyptus grandis)* × *Eucalyptus urophylla*
15	*(Eucalyptus camaldulensis* × *Eucalyptus grandis)* × *Eucalyptus urophylla*
16	*Eucalyptus urophylla* × *Eucalyptus pellita*

2.2. Analytical procedures

For the analysis of wood chips, sawdust and brown pulp, the parameters described in table 2 were

Table 2 – Parameters and their respective methodologies for the characterization of clones of *Eucalyptus* and *Corymbia*.
Tabela 2 – *Parâmetros e suas respectivas metodologias para caracterização de clones de* ***Eucalyptus*** *e* ***Corymbia****.*

Parameter	Procedure
Extractives	TAPPI T 264 cm-97
Carbohydrates	Wallis et al. (1996)
Soluble lignin	TAPPI UM 250
Insoluble lignin	Effland (1977)
S/G	Lin and Dence (1992) modified
Basic Density	ABNT. NBR-11941
Effective alkali	SCAN N2:88
Kappa Number	TAPPI T 236 om-99
Screened yield	Gravimetry

used. EA consumption ($EA_{\#k19}$) and screened yield ($SY_{\#k19}$) for kappa number 19 ± 1 were estimated from three modified kraft pulping tests, in which the applied EA charge was varied and the other conditions were maintained constant. PAGR was calculated as the product of average growth rate, screened yield of pulp, and basic density of wood chips samples. Samples were ranked according to the PAGR/SWC ratio, both estimated using modified pulping to kappa number 19 ± 1. For chemical characterization, the 6 best ranked clones will be selected.

3. RESULTS

Corymbia citriodora × *Corymbia torelliana* wood chips (IDs 1 and ID 4) had the highest basic density (Table 3). The second highest density (0.582 t m^{-3}) was that of *Eucalyptus cloeziana* (ID 5). The lowest basic density was observed for clones ID 11 and ID 14, (*Eucalyptus camaldulensis* × *Eucalyptus grandis*) × *Eucalyptus urophylla*.

C. citriodora × *C. torelliana* (ID 3) had the lowest $EA_{\#k19}$ consumption (15.4%) (Table 2), whereas ID 4 had the highest $SY_{\#k19}$ (54.1%). *E. cloeziana* (ID 5) had the worst performance (49.8%), as it required the highest EA charge, consequently affording the lowest yield.

The highest PAGR value was observed for *C. citriodora* × *C. torelliana* (ID 4), followed by *E. urophylla* × *Eucalyptus* spp. (ID 8), with 24.6 and 17.5 ADt ha^{-1} $year^{-1}$, respectively. The lowest PAGR was observed for a clone of *C. citriodora* × *C. torelliana* (ID 1), with 10.3 ADt ha^{-1} $year^{-1}$. Furthermore, ID 4 exhibited the lowest SWC (2.74 m^3 ADt^{-1}). Thus, ID 4 was ranked first, as it obtained the highest PAGR and lowest SWC values.

For chemical characterization, the 6 best ranked clones in table 3 were selected. The wood chemical composition analysis is essential since the knowledge of such characteristics helps the establishment of production parameters of pulp (Fantuzzi Neto, 2012).

Table 3 – Results for basic wood density (BD), effective alkali (EA), screened pulp yield (SY), average growth rate (AGR), pulp average growth rate (PAGR), and specific wood consumption (SWC) of genetic stocks, as estimated using a kappa number of 19 ± 1.
Tabela 3 *– Resultados para densidade básica da madeira (BD), álcali efetivo (EA), rendimento depurado (SY), incremento médio anual (AGR), incremento médio anual de celulose (PAGR) e consumo específico de madeira (SWC) dos materiais genéticos, utilizando um número kappa de 19 ± 1.*

ID	BD ($t\ m^{-3}$)	EA (%)[1]	SY (%)[1]	AGR ($m^3\ ha^{-1}\ year^{-1}$)[2]	PAGR ($ADt\ ha^{-1}\ year^{-1}$)[3]	SWC ($m^3\ ADt^{-1}$)[3]	Ranking Score[4]
1	0,608 A	16,1	52,5	29,0	10,3	2,82	3,65
2	0,565 C	15,9	51,6	34,8	11,3	3,09	3,66
3	0,507 D	15,4	53,5	51,8	15,6	3,32	4,7
4	0,608 A	16,0	54,1	67,4	24,6	2,74	8,98
5	0,582 B	18,9	49,8	45,9	14,8	3,1	4,77
6	0,518 D	16,0	52,7	37,2	11,3	3,3	3,42
7	0,472 F	15,8	53,6	46,0	12,9	3,56	3,62
8	0,491 E	15,8	53,8	59,6	17,5	3,41	5,13
9	0,470 F	15,6	53,2	42,2	11,7	3,6	3,25
10	0,511 D	16,6	51,1	39,5	11,5	3,45	3,33
11	0,431 G	16,8	51,1	48,2	11,8	4,09	2,89
12	0,470 F	16,9	52,5	46,7	12,8	3,65	3,51
13	0,488 E	17,3	50,9	53,6	14,8	3,62	4,09
14	0,431 G	16,6	51,9	47,6	11,8	4,02	2,94
15	0,519 D	17,6	50,8	40,0	11,7	3,41	3,43
16	0,471 F	17,6	51,1	55,1	14,7	3,74	3,93

Values with the same letters (A - F) within the columns do not differ significantly at α = 0.05. Tested using ANOVA and post-hoc Tukey.
[1] Modified kraft pulping at an H-factor of 1,031, as described in Section 2.1.
[2] Average growth rate of wood volume under bark.
[3] Values for brown pulp.
[4] Ranking was based on the PAGR/SWC ratio.
Valores com as mesmas letras (A - E), dentro das colunas, não diferem significativamente em α = 0,05. Testado usando ANOVA e post-hoc Tukey.
[1] Polpação kraft modificada com Fator-H de 1,031, conforme descrito na seção 2.1.
[2] Incremento médio anual de madeira sem casca.
[3] Valores para polpa marrom.
[4] Ranking baseado na relação PAGR/SWC.

Table 4 – Sawdust Chemical Composition of the 6 best ranked clones.
Tabela 4 *– Composição química da serragem dos 6 clones melhores ranqueados.*

ID	Soluble lignin	Insoluble lignin	Total lignin	Extractives	S/G	Carbohydrates				
						Ara[1]	Gal[2]	Glyc[3]	Xil[4]	Man[5]
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
3	2,6	21,5	0,88	3,62	3,62	0,7	1,3	48	13,2	0,4
	2,92	19,8	22,72	0,77	3,62	0,6	1,2	48,2	13,3	0,4
Average	**2,76 AB**	**20,65 C**	**23,41 C**	**0,83 C**	**3,62 A**	**0,65 A**	**1,25 C**	**48,1 BC**	**13,25 B**	**0,4 D**
4	2,82	20,23	23,05	1,18	2,7	0,6	0,7	48,5	15,3	1,1
	2,94a	20,33	23,27	1,29	2,69	0,6	0,7	48,6	15,3	1,1
Average	**2,88 A**	**20,28 C**	**23,16 C**	**1,24 BC**	**2,7 B**	**0,6 AB**	**0,7 D**	**48,55 B**	**15,3 A**	**1,1 A**
5	1,97	26,43	28,4	2,38	2,09	0,4	1,8	50,1	10,1	0,6
	2,15	26,4	28,55	3,45	2,09	0,5	1,8	50,5	10,1	0,7
Average	**2,06 BC**	**26,42 A**	**28,48 A**	**2,92 A**	**2,09 E**	**0,5 B**	**1,8 A**	**50,3 A**	**10,1 E**	**0,7 BC**
8	2,63	23,67	26,3	2,48	2,48	0,1	1,2	48,2	11,3	0,6
	2,18	23,8	25,98	2,34	2,5	0,1	1,2	48,1	11,2	0,6
Average	**2,41 ABC**	**23,74 B**	**26,14 B**	**2,41 AB**	**2,49 D**	**0,1 C**	**1,2 C**	**48,15 BC**	**11,3 C**	**0,6 BC**
13	2,42	26,3	28,72	1,7	2,64	0,5	1,6	49,9	10,2	0,5
	2,53	26,33	28,86	1,54	2,66	0,5	1,6	49,5	10,2	0,5
Average	**2,48 ABC**	**26,32 A**	**28,79 A**	**1,62 ABC**	**2,65 C**	**0,5 AB**	**1,6 B**	**49,7 A**	**10,2 E**	**0,5 CD**
16	1,98	25,8	27,78	0,72	1,97	0,1	0,8	47,54	11	0,8
	1,65	25,77	27,42	1,18	1,97	0,1	0,8	47	10,9	0,7
Average	**1,82 C**	**25,79 A**	**27,6 AB**	**0,95 C**	**1,97 F**	**0,1 C**	**0,8 D**	**47,25 C**	**11 D**	**0,8 D**

Values with the same letters (A - E) within the columns do not differ significantly at α = 0.05. Tested using ANOVA and post-hoc Tukey.
[1] Arabinanas
[2] Galactans
[3] Glycans
[4] Xylans
[5] Mananas
Valores com as mesmas letras (A - E), dentro das colunas, não diferem significativamente em α = 0,05. Testado usando ANOVA e post-hoc Tukey.
[1] Arabinanas
[2] Galactanas
[3] Glicanas
[4] Xilanas
[5] Mananas

The chemical characterization of the samples is described in Table 4.

The results above are consistent with the wood behavior in pulping process. The lowest total lignin values content was found in clones ID 3 and ID 4 and the highest in clones ID 5, ID 13 and ID 16. The removal of lignin, which is the main objective of the pulping process, releases the portion of wood fibers. Therefore, a low lignin content in wood favors pulping performance and saves chemicals. In addition, delignification is favored when there is a higher S/G ratio (Vidaurre, 2010). The clone that presented the highest S/G ratio was sample ID 3, which is consistent with the lowest consumption of $EA\%_{\#K19}$. The lowest S/G ratio was obtained for the clone ID 16 sample. Consequently, shown a lower performance in the kraft pulping process compared to the others ranked, despite having a lowest total lignin content.

Extractives had lower values in clones ID 3, ID 4, ID 13 and ID 16. In general, extractives impair pulping performance by causing scaling problems in equipment, pipes and tanks, forming pitch (Mokfienski et al. 2008). High levels of extractives content could impact negatively in the impregnation process and in the chemical consumption, additionally interfere negatively in the yield. The carbohydrate content has similar values to those reported in the literature (Mokfienski et al. 2008). Clones ID 5 and ID 13 had the highest glycan value and the lowest xylan content.

4. DISCUSSION

The results of this study revealed the potential of *Corymbia* spp. wood in pulp production and the relationship between basic wood density, EA consumption, and screened yield. By applying the modified kraft pulping protocol, we were able to combine optimal temperature and time conditions to obtain the best yields without requiring a high alkali charge for the samples with the highest density (ID 1 and ID 4).

There was a positive impact of higher basic density on SWC in *Corymbia* spp. In particular, *C. citriodora* × *C. torelliana* (ID 4) showed excellent performance in forest productivity and kraft pulping, affording good $EA_{\#k19}$ and $SY_{\#k19}$ values. Basic density is used to select genetic stocks according to the intended purpose and is a relevant parameter for standardization of raw materials received by the industry (Souza et al., 2017). High wood density is generally associated with increased yield, reduced logistics costs, low SWC, and low EA (Jardim et al., 2017).

Another important aspect to be discussed is the SWC during production, given that, in addition to being directly related to density and yield, it is also associated with several wood quality parameters (Gallo et al., 2018). *Corymbia* hybrids exhibited the SWC values lower than *Eucalyptus*. Such a finding can be explained by the high density of these samples, as denser woods have more cellulose, favoring yield. In other words, smaller volumes of wood would be required for the production of a unit weight of pulp (Gomide et al., 2010).

The particularity of each species and clone was analyzed considering PAGR values. The results demonstrated the potential of clone ID 4 in the forestry, pulp, and paper industries. PAGR takes into account wood volume, basic density, and yield, reflecting the amount of pulp that can be produced (Souza et al., 2020). Leading companies in the pulp and paper industry in Brazil report average PAGR values of 10 to 12 ADt of bleached pulp per hectare per year (Foelkel, 2017). Here, ID 4 achieved a PAGR of 24.6 ADt ha^{-1} $year^{-1}$, indicating that this clone may be a good choice for commercial applications aimed at high performance in forest and pulp industries.

After chemical analysis of sawdust from the top 6 ranked clones, it was found that *Corymbia* spp. clone ID 3 has a higher S/G ratio and clone ID 4 has a higher xylan content compared to *Eucalyptus* clones. Respectively, these chemical composition could be positive in the pulp bleachability and on the beatability of bleached kraft pulps.

5. CONCLUSIONS

This work evaluated and compare different samples of *Eucalyptus* spp. and *Corymbia* spp. on their performance based on key forestry and industrial parameters. Ideally, commercial clones should be ranking, based at least on PAGR and SWC. Industrial kraft pulping protocols should be the accurately choice, in order to minimize differences between laboratory and industrial conditions.

Clone ID 4 (*C. citriodora* × *C. torelliana* hybrids), were the highest-ranked, proving to be excellent high-performance alternative for forest-industry interface parameters. Higher wood basic density shown a clear advantage with regard to SWC (m^3 ADt^{-1}), consequently lower production costs per air dry ton of pulp (US$ ADt^{-1}). Clone ID 4 meet higher value of SWC since, simultaneously present higher value of wood basic density and screened yield.

Regardless, *Corymbia* spp. hybrids wood chemistry composition, Clone ID 3 confirmed lowest $EA_{\#K19}$ consumption value, much associated to the higher S/G ratio. Clone ID 4 shown one of the lowest total lignin content, consequently highest screening yield. Besides Clone ID 4 shown significantly highest xylan content, among wood sample assessed in this work.

Furthermore, as further work, it will be interesting to evaluate these 6 top clones, regarding ECF bleaching, fiber morphology characterization and bleached pulp physico-mechanical properties.

AUTHOR CONTRIBUTIONS

Conceptualization and research design: Costa, M.M.; Writing, review and editing: Nogueira, A.P.C.; Bittencourt, R.C.; Formal analysis: Silva, W.H.M.; Silva, L.S.; Almeida, R.F.; Data collection: Santos, G.A.; Pena, C.A.A

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