Chapter

Wood Quality and Pulping Process Efficiency of Elite *Eucalyptus* spp. Clones Field-Grown under Seasonal Drought Stress

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Abstract

The objective of the present study is to evaluate the wood quality of five elite *Eucalyptus* spp. clones at 4 years of age from a clonal test installed in a region of seasonal drought stress in central-western Brazil focusing on pulp production. A total of 25 trees were systematically felled and disks and logs were obtained along the trunk. Wooden disks were used for density and fiber analyses and the logs were converted into chips for application in the pulping process. For the denser genotype, clone D (*E. grandis* x *E. urophylla* x *Eucalyptus tereticornis*), a thicker cell wall associated to thinner fibers results in a negative effect on the fiber quality. In contrast, clone B (*Eucalyptus pellita* x *E. grandis*), which has relatively inferior pulping performance, displayed the lowest wood density associated to wider lumen and fibers. The best growth performances in response to acclimatization and adaptation to the site strongly influences the pulp productivity, which is identified as the parameter of greatest variance between genotypes, and highlighting clone E (*E. grandis* x *E. urophylla*).

Keywords: clonal test, kraft pulp, wood technology, fiber, density

1. Introduction

Brazil is among the world's largest pulp and paper producers and has developed studies aimed at increasing knowledge on forest-to-product raw materials in an attempt to meet the growing demands and economic interest. *Eucalyptus* trees are the most common hardwood fiber sources for chemical cellulose and paper production in Brazil, with a minimum harvesting age of approximately 4.5 years and average yield of 35 m^3 h^{-1} yr^{-1} [1]. This major industrial-scale interest has led to a steady increase in the extent of *Eucalyptus* plantations, which has been moved to new frontiers such as north and central-western regions of Brazil. These new frontiers are predominantly characterized by dystrophic soils and very distinct seasonal rainfall compared with traditional regions. The climatic condition specifically for the central-western region is marked by seasonal drought stress of about 5 months [2].

It is well known that water deficit is one of the most challenging factors of our times which threatens *Eucalyptus* plantation production [3]. A slight reduction in average *Eucalyptus* yield was observed in Brazil compared to previous years as a result of advancing planted areas to regions where water deficits are more severe [4]. However, little has been explored regarding the extent of the potential impacts on the wood quality for end use. From that understanding and considering that extreme drought events will happen more frequently around the world [5], new studies aligned to increase knowledge on the changes in forestry which go beyond the influence on stand volume are intended.

Eucalyptus wood characteristics may vary substantially among species and clones [6, 7], as well as by the plantation site [8–10]. Wood density and cellular structure of xylem are highly associated when considering the wood characteristics related with adaptation mechanisms to drought [11, 12]. There is a close relationship between density and hydraulic safety in the sense that a greater resistance to the cavitation process (better hydraulic safety) is related to higher wood density [13]. This in turn could be explained by changes in the structure of vessel elements [13], and/or by the contribution that the fiber matrix (non-conductive elements) makes to adjust the necessary equilibrium during water transport under high tension [14]. Hence, since the wood quality for pulp production is strongly influenced by anatomy and density properties [15, 16], the extent to which these adaptive responses determine pulp and papermaking performance has economic relevance [17].

The *Eucalyptus grandis* x *Eucalyptus urophylla* hybrid has been widely used in Brazil, providing most of the raw material which is used for hardwood pulp companies [18]. Additionally, interspecific hybrids from species such as *E. grandis*, *E. urophyla*, *Eucalyptus camaldulensis*, *Eucalyptus pellita* and *Eucalyptus tereticornis* have been utilized as a strategy for dry environments [19]. Researchers in a public-private partnership have installed an unprecedented breeding program with several *Eucalyptus* species and hybrids in Goiás state, in the central-western region of Brazil. The objective has been to evaluate the performance of different genetic materials against specific climate and soil conditions, aiming to select superior clones to compose future plantations on an industrial scale in these new *Eucalytpus* plantation frontiers in the country. Therefore, the present work evaluated five elite *Eucalyptus* clones at four-year-old grown in Goiás state, Brazil, regarding their wood properties and their impact on morphological quality indices and pulping process efficiency. The overall objective was to indicate the pulpwood potential of superior genetic materials adapted to the Brazil central-western region, contributing to increase knowledge of drought-tolerant genetic materials available for the pulp and paper industry.

2. Materials and methods

2.1 Site and wood sampling

Five elite *Eucalyptus* spp. clones at 4 years old were selected from a clonal trial located in Goiás State, central-western Brazil (16° 16′ 37″ S; 47° 44′ 02″ W; 930 m

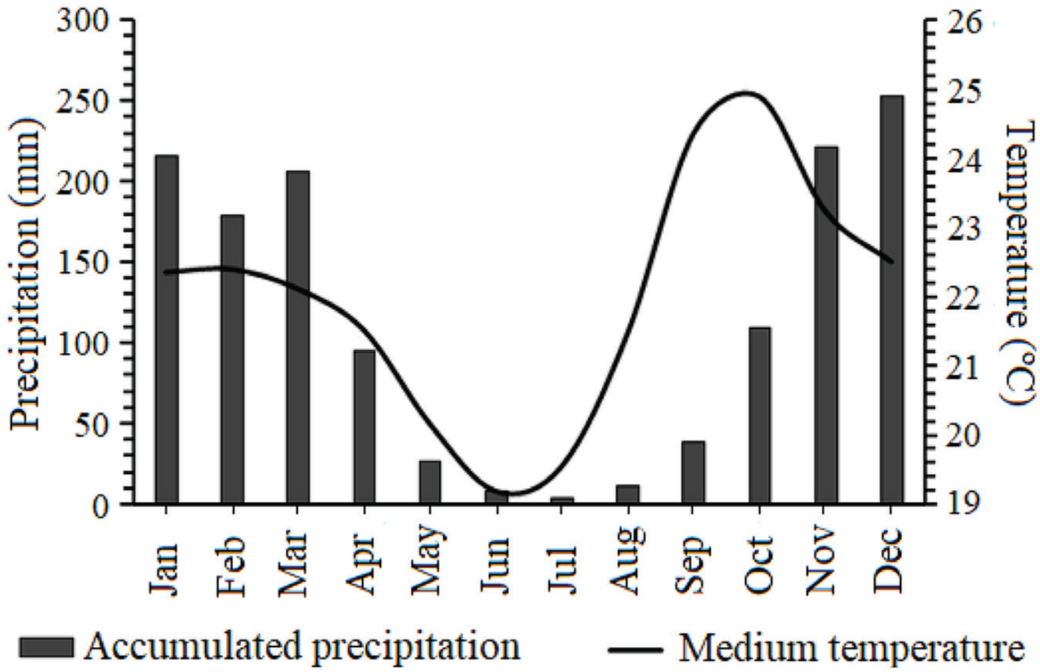

Figure 1.
Climatological normal (1990–2020) of temperature (°C) and accumulated precipitation (mm) of Luziânia, Goiás, Brazil - NASA power climate data.

above sea level). The experiment was established in December 2012, with 93 *Eucalyptus* species/hybrids, using single tree plots and 29 replications. Trees were planted at 3.0 × 3.0 m spacing and were managed according to the operational practices for *Eucalyptus* plantations in Brazil (i.e., with limestone and NPK fertilization, and control of weeds and ants). According to the Köppen-Geiger climate classification, the region's climate is subtropical humid with dry winters and wet summers [20]. The mean annual rainfall is near 1300 mm with five dry months per year, and the annual average temperature is 22.0°C (**Figure 1**). The soil is Plinthosol, being characterized as gravelly with an acidic pH, low base saturation and high aluminum saturation.

A total of 25 trees were systematically felled (five genotypes, five trees each). The selected clones were among the most productive of the experiment and are hybrids from a diversity of species. **Table 1** shows the species, growth and wood properties obtained from disks at breast height of five elite *Eucalyptus* clones. The wood disks for this work were obtained at five different Heights (base, 25%, 50%, 75% and at 100% of the commercial height) for determining basic density and fiber characteristics. In addition, wood logs of approximately 50 cm were obtained at intermediate heights regarding those previously mentioned. These logs were chipped into small sized pieces (around 5 mm) and kept stored before kraft pulping. **Figure 2** illustrates the sampling process and respective analysis.

2.2 Fiber morphology and basic wood density

Blocks of approximately 1 cm^3 were sampled along the radius for fiber measurements from the pith to bark. Block samples were macerated with acetic acid and hydrogen peroxide, stained with Safranin and assembled in microscope slides. Images were obtained using a Zeiss Axio Scope A1 microscope and a digital camera (Canon A640). The length, diameter, wall thickness, and lumen width of fibers were

Clone	Genotype/hybrid	MAI	VA	SL	TL	HOL	EXT	ASH
		m^3 h^{-1} yr^{-1}			%			
A	Spontaneous hybrid *E. urophylla*	50.9	11.8	3.5	27.5	66	6.3	0.25
B	*Eucalyptus pellita* x *E. grandis*	49.1	12.6	3.5	28.3	65.9	5.5	0.4
C	*Eucalyptus camaldulensis* x *Eucalyptus tereticornis*	34.6	14.4	3.4	28.4	66.2	5.1	0.34
D	*E. grandis* x (*E. urophylla* x *E. tereticornis*)	48.7	11.2	3.2	27.9	68	3.7	0.4
E	*E. grandis* x *E. urophylla*	68.3	12.2	3.6	28.6	66.5	4.6	0.35

MAIvol–mean annual volume increment; VA–vessels area; SL–soluble lignin; TL–total lignin; HOL–holocellulose; EXT–extractive contents.

Table 1.
Species, productivity, vessels area and chemical composition of wood of the five selected Eucalyptus *elite-clones.*

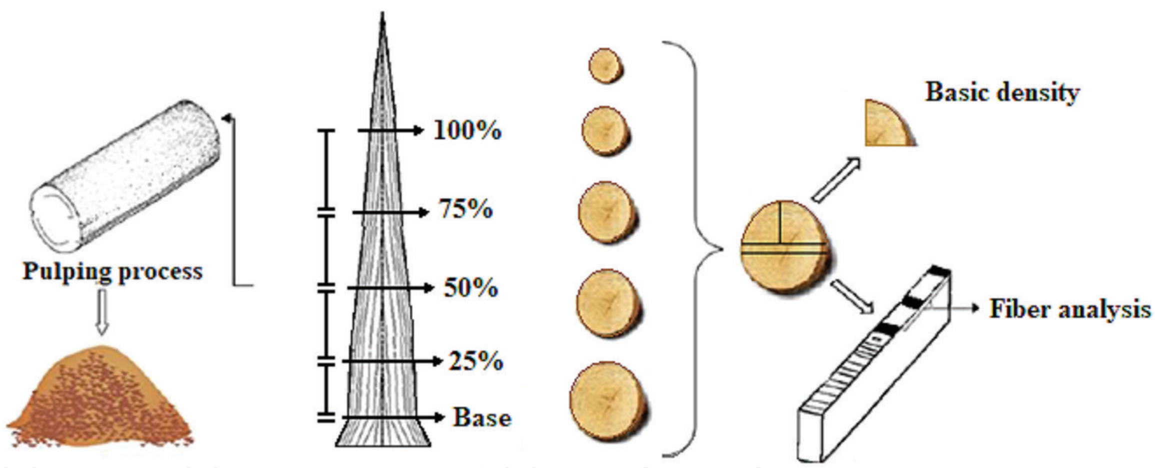

Figure 2.
Sampling process and respective analysis of the Eucalyptus clones wood.

measured using the Image Pro-Plus Software (version 5.0) program as recommended by International Association of Wood Anatomists (IAWA) [21].

Next, relationships were established between individual fiber dimensions and quality indices to evaluate the wood morphological properties for paper purposes, such as the Runkel ratio, wall proportion, flexibility coefficient, slenderness ratio and Luce's shape factor. These indices were analyzed according to the categories established by Barrichelo and Brito [22] and Foelkel et al. [23], and calculated according to the following equations:

$$Runkel\ ratio\,(RR) = 2w\,/\,d \tag{1}$$

$$Wall\ proportion\,(WP) = (2x\,/\,D)\times 100 \tag{2}$$

$$\text{Flexibility coefficient}\,(FC) = d / D \tag{3}$$

$$\text{Slenderness ratio}\,(SR) = L / D \tag{4}$$

$$\text{Luce'shape factor}\,(LSF) = \left(D^2 - d^2\right) / \left(D^2 + d^2\right) \tag{5}$$

In which: w is the cell wall thickness, D is the fiber diameter, d is the fiber lumen width, and L is the fiber length.

The basic wood density was determined according to ASTM D2395–17 using wood wedges (approximately 1/4) obtained from each disk.

2.3 Pulping process

All pulping processes were performed in triplicate in a rotating digester containing eight capsules with capacity of 10 L. An alkaline curve with four active alkali levels was performed under fixed kraft pulping conditions for each genotype (**Table 2**). The alkali levels were selected from previous tests in order to determine the dosage of active alkali (AA) required to obtain a kappa number 18.0 ± 0.5. The analysis of residual alkali in black liquor was performed according to SCAN-N 2:88 modified. Pulp yields and consumed alkali (difference between applied and residual alkali) were calculated, and the pulps' kappa number was determined according to TAPPI T 236 om-99. The other calculated parameters were wood specific consumption [24] and mean annual pulp increment [15], according to the following equations:

$$WSC = \frac{1}{BD \times PY} \times 0.9 \tag{6}$$

in which: WSC = wood specific consumption ($m^3\ t^{-1}$); BD = basic density ($g\ cm^{-3}$); PY = pulp yield (in decimal).

$$MAIpulp = \frac{MAIvol \times BD\ x\ PY}{1111} \tag{7}$$

in which: MAIpulp = mean annual increment of pulp ($t\ h^{-1}\ yr^{-1}$); MAIvol = mean annual increment of volume ($m^3\ h^{-1}\ yr^{-1}$); BD = basic density ($kg\ m^{-3}$); PY = pulp yield (%).

Parameter	Condition
Active alkali, % (NaOH based)	22, 24, 26 e 28
Sulphidity, %	25
Dry chip mass, g	70
Relation liquor/wood	04:01
Maximum temperature, °C	166
Time at maximum temperature, min	90
Heating time, min	60
H factor	780

Table 2.
Kraft pulping conditions.

2.4 Data analysis

The data were submitted to normality [25] and homogeneity tests of residual variances [26]. The effect of genetic variation between clones was evaluated for all the quantified wood variables by univariate analysis of variance (ANOVA). The averages were compared by the Tukey test (α = 0.05) when the effect of clones was significant, except the morphological ratios which were descriptively analyzed. The kraft pulping properties were evaluated using linear and polynomial regression models [27], where Y represents the kappa number, yield or consumed alkali, and Xi the alkali charge used. Pearson's correlations were used to examine expected relationships between wood properties. A principal component analysis (PCA) was also performed to recognize the most important parameters for the studied clones and their relationships. The analysis was performed using a correlation matrix with 95% statistical significance. The 95% ellipse limits were also used to test the variables in relation to the clones [28].

3. Results

3.1 Wood characteristics

The average values of fiber dimensions, morphological ratios and basic density are summarized in **Table 3**. Fiber morphology showed considerable differences between genotypes, except for length measurements. Fiber length corresponded from 813.6 μm (clone E) to 836.6 μm (clone D); fiber diameter from 16.9 μm (clone D) to 18.5 μm (clone B); fiber wall thickness from 3.8 μm (clone B) to 4.5 μm (clone D); and lumen width from 8.0 μm (clone D) to 10.9 μm (clone B).

Clone	Wood				Fibers ratio					BD
	FL	FD	FWT	FLW	RR	WP	FC	SR	LSF	
	(μm)					(%)				(kg m^{-3})
A	833.2^{a}	18.1^{a}	4.4a	9.4^{b}	1.05	50.2	0.50	45.9	0.58	489^{ab}
	(11.8)	(5.3)	(16.4)	(14.3)	(9.6)	(3.4)	(3.1)	(4.5)	(3.4)	(6.1)
B	834.4^{a}	18.5^{a}	3.8^{b}	10.9^{a}	0.76	43.5	0.57	45.5	0.49	446^{b}
	(8.2)	(11.2)	(16.9)	(10.0)	(8.7)	(5.0)	(3.5)	(5.9)	(5.5)	(5.1)
C	815.3^{a}	17.8^{ab}	4.1^{ab}	9.5^{b}	0.93	48.7	0.52	46.0	0.56	472^{ab}
	(8.1)	(5.1)	(13.6)	(10.7)	(15.4)	(9.0)	(7.9)	(3.0)	(9.7)	(3.3)
D	836.6^{a}	16.9^{b}	4.4^{a}	8.0^{c}	1.19	54.8	0.46	49.7	0.64	501^{a}
	(9.5)	(5.1)	(18.4)	(12.6)	(17.5)	(8.0)	(8.9)	(2.8)	(8.2)	(2.8)
E	813.6^{a}	18.2^{a}	4.2^{ab}	9.9^{b}	0.92	49.7	0.55	44.8	0.55	495^{a}
	(8.6)	(4.2)	(9.6)	(6.1)	(9.2)	(5.0)	(4.2)	(3.7)	(5.4)	(4.1)

FL–fiber length; FD–fiber diameter; FWT–fiber wall thickness; FLW–fiber lumen width; RR–Runkel ratio; WP–Wall proportion; FC–flexibility coefficient; SR–slenderness ratio; LSF–Luces's shape factor; BD–basic density. Means and coefficients of variation (%). Means followed by the same letter do not differ from each other by the Tukey test (p > 0.05).

Table 3.
Fiber dimensions, morphological ratios, and basic density of the five elite Eucalyptus spp. clones.

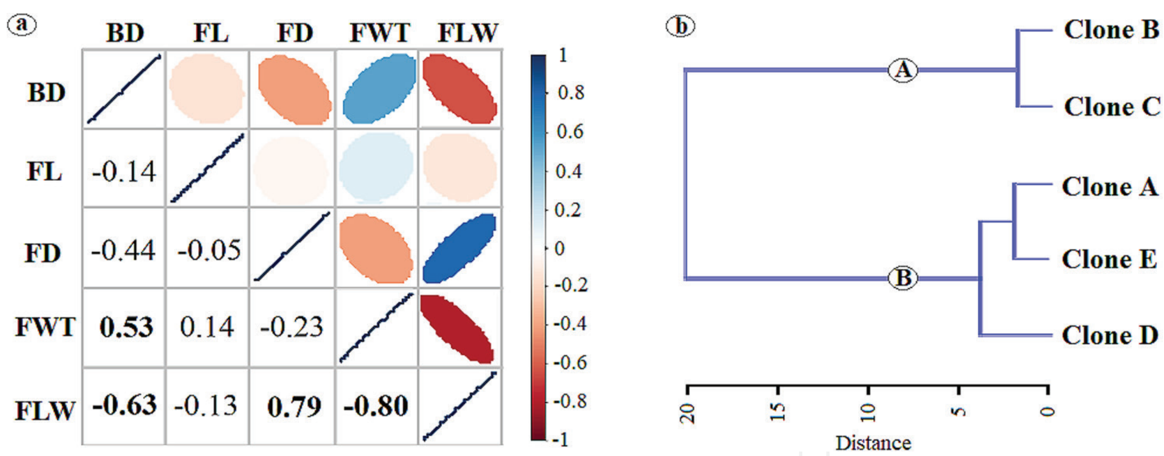

Figure 3.
Pearson's correlation (a) and hierarchical cluster analyses (b) for fiber dimensions and wood density of Eucalyptus *spp. clones. BD–basic density; FL–fiber length; FD–fiber diameter; FWT–fiber wall thickness; FLW–fiber lumen width.*

Regarding the morphological ratios, clone B had the lowest RR (Runkel ratio), WP (wall proportion) and LSF (Luce's factor): 0.76, 43.5%, and 0.49, respectively. The highest values for the same ratios were found for clone D (1.19 to RR, 54.8 to WP and 0.64 to LSF). In the same way but with opposite results, clone B showed the highest flexibility coefficient (0.59), and clone D presented the lowest value (0.46). Slenderness ratio values ranged from 44.8 (clone E) to 49.7 (clone D).

Mean wood density ranged from 446 to 501 kg m^{-3}, with the highest basic density for clones D and E and differing significantly between clone B. In **Figure 3a** it can be verified that wood density presented a significant inverse correlation with the fiber lumen width (p-value = 0.006) and a positive correlation with fiber wall thickness (p-value = 0.02). Correlations are also verified between fiber diameter and fiber wall thickness (p-value <0.001) and between fiber wall thickness and fiber lumen width (p-value <0.001). Taking to account the fiber dimensions and basic density, cluster analysis showed the formation of two main groups (**Figure 3b**). Group 1 comprised clones B and C, while group 2 contained clones A, D and E.

3.2 Kraft pulping properties

Figure 4 shows the graphs and equations established to mathematically determine the alkali charge to obtain the kappa number ±18. **Table 4** presents these corresponding values, as well as other technological parameters calculated for the target kappa. Clones decrease the kappa number at an average range rate of 8% (clone D) to 13% (clone A). In the pulp delignification degree for Kappa ±18, the wood from the five genotypes produced pulps with distinct characteristics, except for pulp yield which did not significantly differ between them with values ranging from 51.3–52.8%. Clone C used the lowest alkali to obtain a kappa number ± 18 (23.2%), significantly differing between clones A and B. Consumed alkali ranged between 32.0–40.6 g L^{-1}, with the lowest value for clone D, and with no significant difference between clone E. Clone C obtained the lowest residual effective alkali value (13.3 g L^{-1}), while clones B and D showed the highest values for this parameter (20.0 and 20.3 g L^{-1}, respectively). Clones A, D and E presented the lowest wood specific consumption, with values close to 3.5 m^3 t^{-1}, and clone E showed the best performance in terms of pulp productivity (MAIpulp = 19.8 t h^{-1} yr^{-1}).

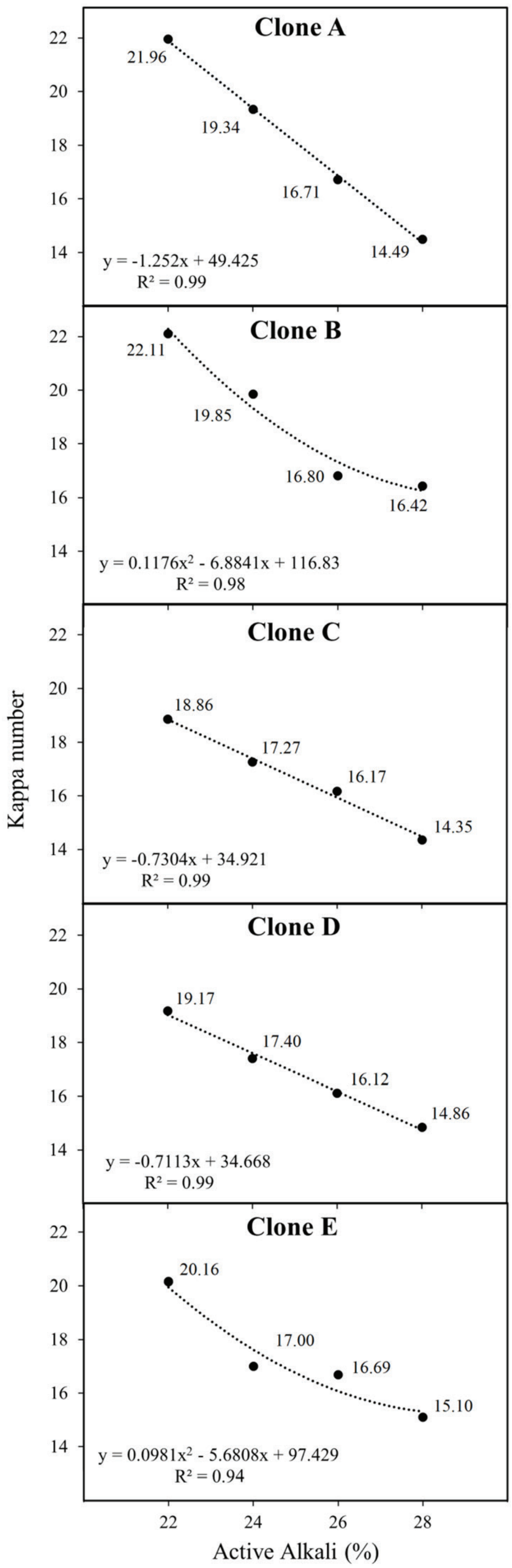

Figure 4.
Kappa number curves as a function of the active alkali applied to the five Eucalyptus *spp. clones. Adjusted-regression for higher correlation coefficient.*

Clone	Alkali charge	Yield	Consumed alkali	REA	WSC	MAIpulp
	%		$g.L^{-1}$		$m^3.t^{-1}$	$t\ h^{-1}\ yr^{-1}$
A	25.1[ab]	52.3[a]	40.6[a]	16.0[b]	3.5[c]	14.7[b]
B	25.5[a]	51.3[a]	38.5[a]	20.0[a]	3.9[a]	12.5[d]
C	23.2[c]	52.8[a]	39.7[a]	13.3[c]	3.6[b]	9.5[e]
D	23.5[bc]	52.7[a]	32.0[b]	20.3[a]	3.4[c]	14.1[c]
E	23.5[bc]	52.2[a]	35.3[ab]	17.0[b]	3.5[c]	19.8[a]

REA–residual effective alkali; WSC–wood specific consumption; MAIpulp–mean annual increment of pulp. Means followed by the same letter in the same column do not differ from each other by the Tukey test ($p > 0.05$).

Table 4.
Kraft pulping characterization for Kappa number ± 18 of the five Eucalyptus *spp. clones.*

3.3 Principal components analysis

Figure 5 shows the ordering of eigenvectors and the measures of similarity between *Eucalyptus* spp. clones. Clones were preserved in their characteristics but showed proximity between them. Regarding the study parameters, MAIpulp, consumed alkali, fiber lumen width and wood specific consumption are those which represented the largest variances in the analysis, determining the distribution of clones and variables. Three main groups of variables were formed: group 1 containing fiber diameter (FD), alkali charge (AC) and fiber lumen width (FLW), negatively related

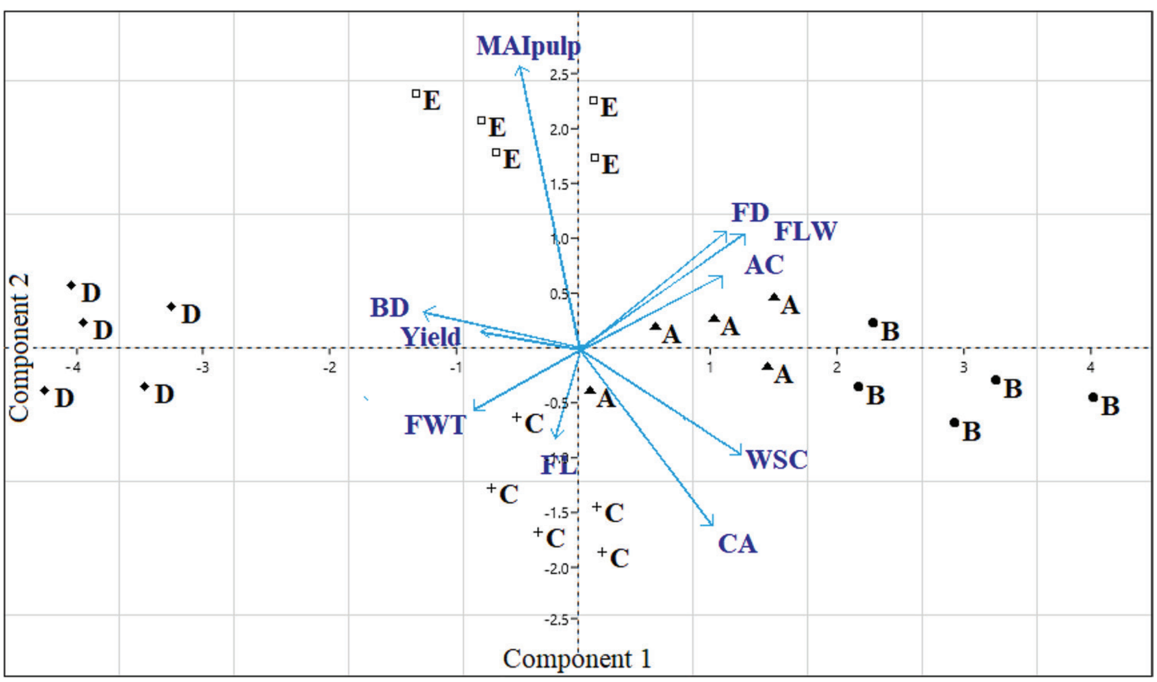

Figure 5.
Principal component analysis of the fiber dimensions, basic density and kraft pulping parameters of the five Eucalyptus *spp. clones. FL–fiber length; FD–fiber diameter; FWT–fiber wall thickness; FLW–fiber lumen width; BD- basic density; AC–Alkali charge; CA–consumed alkali; WSC–wood specific consumption and MAIpulp–mean annual pulp increment (significant variables according to Boot N x 10.000 criteria and their percentage of variance; MAIpulp −69.9%; CA – 45.2%; FLW- 42.7%; WSC – 37.5%).*

to clone D; group 2 formed by consumed alkali (CA) and specific wood consumption (WSC) directly related to clone B, and inversely to clone D; and group 3 formed by yield, fiber wall thickness (FWT) and basic density (BD) directly related to clones D, and negatively to clone B.

4. Discussion

4.1 Wood traits demonstrate significant variations among genotypes

Although there is a clear association between climate and wood properties, genetic factors influence their expression [5, 29] and shape the adaptive responses [30, 31]. This explains why the best performing *Eucalyptus* clones (elite clones) selected for this study are genetic materials which have relative drought tolerance [4, 31]. Thus, a selection metric of *Eucalyptus* clones based on traits for drought tolerance and high productivity combined with versatile wood properties for pulp and paper offers a good perspective for the current world pulp and paper industry.

Similar fiber dimensions were reported in the literature for young *Eucalyptus* trees with fiber length between 670 and 1040 μm, fiber diameter between 16 and 19 μm, fiber wall thickness between 3 and 5 μm and lumen width between 7 and 9.5 μm [16, 32, 33]. Wood-fiber characteristics are among the first indicators to be evaluated for screening potential fibrous raw materials for paper production. Fiber dimensions are generally related to collapsibility and flexibility properties, which are strongly associated with paper strength and surface properties [34, 35].

The lowest values presented by clone B for RR, WP and LSF is related to the fact that this genotype has comparatively thin walled fibers. It is assumed that an RR value less than 1.0 is favorable to produce an inter-fiber contact in manufacturing paper using hardwoods, and greater than 1.5 is not recommended. Percentages below 60% are indicated for the wall proportion, while Luce's factor is a ratio related to the final paper sheet density and can be used for specific selection [22, 23]. In this sense, all clones have adequate wall proportion, and clones B, C and E presented better RR values. According to [36], flexibility coefficient values between 0.50–0.75, as verified in this study (except for clone D), classify the fibers as flexible, which tend to form a highly resistant paper when intertwined. Finally, the slenderness ratio is a quality directly related to paper tear index, for which values above 50 are preferable. None of the clones showed a higher value as indicated, with clone D being the highest.

The values presented for basic wood density must be classified as average, meaning 450–540 kg m^{-3}, considered acceptable for commercial pulpwood and are similar to previous reports for young *Eucalyptus* trees between 450 and 500 kg m^{-3} [37, 38]. According to Gomide et al. [39], the projects to increase production capacity and to deploy new factories have prioritized the use of wood with a density close to 500 kg m^{-3}, as verified for the study clones, with an emphasis on clones D (*E. grandis* x *E. urophylla* x *Eucalyptus tereticornis*) and E (*E. grandis* x *E. urophylla*).

Significant correlations between fiber dimensions and density reflect the intrinsic.

association between these properties. Barroto et al. [11] suggest a mediated effect of fiber wall fraction on the functionality of *Eucalyptus* trees through vessel dimensions and basic density. It is possible to note that clone D displayed higher fiber wall proportion and wood density, however it also had the lowest vessel area (see **Table 1**). Thus, a disadvantage is verified for this clone in terms of fibrous raw materials (quality indices), although the higher average density results in lower wood specific consumption. Similar behavior can be observed for clone A (*E. urophylla*).

4.2 The evaluated clones show potential for cellulose pulp in central-western Brazil

Despite the large variation observed in wood properties, it is possible to affirm that all *Eucalyptus* clones presented quality as raw material to make paper and good pulping performance. The alkali charge values found in the literature for approximate target kappa are lower than those presented in this study [40, 41]. However, Gomide et al. [42] cites alkali percentages between 20.1 and 23.7% for kappa ±18 in assessing 75 wood samples of *Eucalyptus* clones from different Brazilian regions, thus evidencing the great variability existing for this technological parameter depending on the genotype and the environmental influences on growth. These high alkali charges required can be due to relatively high extractive content presented by genotypes (see **Table 1**), which increases the active alkali demand for pulping the wood to a given kappa number [43, 44].

Increasing pulp yield is a major goal of a chemical process, being related to the reduction of residual effective alkali (REA) at the end of cooking [45]. In this sense, higher value of consumed alkali represents better kraft pulping performance. Although the five *Eucalyptus* clones showed similar yield values, the same was not observed for the consumed alkali and residual effective alkali rates. According to Ribeiro et al. [45], the REA varies between 4 and 18 g L^{-1} considering different mills, while the range of 7–9 g L^{-1} is more common. Given this, the result is that the clones B and D reached high values for this parameter. Segura et al. [46] presented consumed alkali values on different levels of kappa number around 35–45 g L^{-1} for *E. grandis* x *E. urophylla* at 6 years old, thus corroborating the results presented herein. For *Eucalyptus* trees grown in southeastern Brazil, Gouvêa et al. [40] mentions pulp yield values from 50.3–52.9%, and Ferreira et al. [47] relates pulp yield values between 50 and 55% for *Eucalyptus* commercial clones at seven-nine years old. Similar results were reported by other authors [48].

The pulping yield directly influences the wood specific consumption - WSC, which in this work, was obtained taking into account only the yield in each pulping, disregarding the losses in the subsequent processes. Segura et al. [46] emphasizes that the basic density, which is an associated key property to wood specific consumption, has an important role in pulping costs and the densest materials present lowest wood specific consumption, reducing the wood and process costs. At the same time, higher densities may imply in low permeability of the wood by the liquor, thereby requiring high chemical usage and energy [49]. This is why density values within a medium range which configure a high proportion of wood in balance with good efficiency in the pulping process is given importance.

The best performance of clone E (*E. grandis* x *E. urophylla*) in terms of mean annual increment of pulp is due the high wood productivity (see **Table 1**, mean annual volume increment), which emphasizes the relevance of this attribute in assessing potential on a large scale. Clone C (*Eucalyptus camaldulensis* x *E. tereticornis*) presented the greatest disadvantage for this parameter. Clone B (*E. grandis* x *Eucalyptus pellita*) presented satisfactory growth in contrast with relatively inferior pulping performance and displayed less dense wood associated to wider fibers and lumen.

As can be seen, variations in the wood properties act dynamically on raw material quality and technological performance of *Eucalyptus* spp. clones. The magnitude of changes in the wood properties in response to the site did not evidence negative impacts on the pulping process efficiency of *Eucalyptus* clones at 4 years in comparison with the literature, except for alkaline charge. With respect to large-scale pulp production, there is a strong influence of growth potential and adaptive capacity of different hybrids. In this sense, the *E. grandis* x *E. urophylla* hybrid having highest wood volume stands out. Finally, the genetic material choice determined by factors which are related to environmental conditions, together with an assessment on the particular parameters related to end-use, as guided by the present study, plays a very important role in efficient breeding selection. However, it is important to emphasize that other traits should be explored in considering the overall assessment of the kraft pulp potential of a wood, such as the cellulose and lignin composition and fiber morphological and handsheet properties.

5. Conclusion

The five elite *Eucalyptus* clones at 4 years generally presented wood quality for pulping or paper end-use with adequate values for most fiber ratios and average basic density. Good technological performance was obtained with respect to pulp yield. In contrast, genotypes presented a high required alkali charge to obtain a kappa number ±18.0 as a disadvantage. Overall, clone E (*E. grandis* x *E. urophylla*) stands out among the analyzed genotypes in terms of combined characteristics. Clone D (*E. grandis* x *E. urophylla* x *E. tereticornis*) presented inferior fiber quality as a consequence of thicker cell wall associated to thinner fibers. Conversely, clone B (*E. pellita* x *E. grandis*), which has the lowest wood density associated to wider lumen and fibers, displayed relatively lower pulping performance.

The prior selection of *Eucalyptus* genotypes with drought tolerance and high productivity traits, associated to the significant variations found among them in this present work for important parameters associated with wood properties and pulpability, represents the basis for an efficient evaluation based on pulp potential in aiming to select genotypes for commercial plantations. Future studies to explore other important quality traits must be performed.

Acknowledgements

The authors acknowledge the Chemistry, Pulp and Energy Laboratory and the Wood Anatomy and Tree-Ring Laboratory of São Paulo University (USP) and the Wood Quality and Bioenergy Laboratory of the Federal University of Goiás.

Conflict of interest

The authors declare no conflict of interest.

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