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Influence of spacing between trees on wood and charcoal quality indicators

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SILVICULTURE

ABSTRACT

Background: The objective of this study was to evaluate the quality indicators for wood and charcoal from the *Eucalyptus urophylla* x *Eucalyptus grandis* hybrid (Clone GG 100) in different planting spacings. The study was conducted with the hybrid using the spacings of 2×1, 2×2, 3×2, and 3×3 m. The chemical properties of wood and charcoal were analyzed, and dry wood mass and energy per hectare were estimated. The data were subjected to the t test for comparison of means. Moreover, principal component analysis was conducted to assess the relationships between wood and charcoal indicators as a function of spacing.

Results: The 2×2 m spacing showed the highest values for dry wood mass, lignin mass, mass of charcoal, and energy. The wider spacings of 3×2 and 3×3 m resulted in wood and charcoal of increased quality by showing wood of greater resistance to thermal degradation and charcoal of higher yield.

Conclusion: Spacing between trees influenced wood quality indicators. The 2×2 m spacing showed higher estimates of mass and energy per hectare. However, wide spacings with an area greater than 6 m^2 are more suitable for charcoal production due to their superior wood properties, especially basic density and total lignin, which influence gravimetric yields and bulk density.

Keywords: *Eucalyptus*; Wood quality; Biomass energy.

HIGHLIGHTS

Tree spacing influenced the quality indices of wood and charcoal.
Lignin and gravimetric yield show highest relative contributions for wood and charcoal.
The 2×2 m spacing presented higher estimates of mass and energy per hectare.
Wider spacings (> 6 m^2) are the most suitable to produce charcoal.

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INTRODUCTION

The environment where trees are planted affect growth, productivity, and, consequently, the quality of final products (Rocha et al., 2016; Simetti et al., 2018). The application of knowledge that relates the growth dynamics of the tree population and the interactions between its individuals favor the production of high-quality products with high conversion efficiency and greater added value (Soares et al., 2016; Pereira et al., 2016; Marchesan et al., 2019).

Silvicultural practices associated with forest management have become alternatives to obtain wood and convert it into different products, such as charcoal, with adequate yield and quality for different purposes (Häggman et al., 2013). The analysis of tree behavior in different planting arrangements and their relationship with the dendrometric characteristics is essential since it guides the selection of wood parameters that are suitable for the desired final product (Tonini et al., 2020).

One strategy for obtaining wood and charcoal with high quality indicators is to seek for the ideal tree planting spacing. To determine the ideal spacing, the number of trees that a forest site can support is inferred. Spacing influences the availability of growth resources such as light, water, and nutrients for plants and should be strategically analyzed by the forester (Resquin et al., 2019; Ramalho et al., 2019).

Modifications in the useful area per plant influence tree growth, wood quality, and the economic aspects of the forestry enterprise, as they alter the tree's volumetric growth and, consequently, the amount of dry wood mass and charcoal per hectare, in addition to estimates of total lignin and stored energy (Rocha et al., 2017), as well as the quality of charcoal (Junior et al., 2016).

Understanding the quality standards of wood and charcoal can help increase production, choose superior genetic materials, and reduce the use of raw materials while maximizing efficiency (Protásio et al., 2014; Silva et al., 2018; Costa et al., 2020). Thus, the objective of this study was to evaluate the quality indicators of wood and charcoal from the *Eucalyptus urophylla* x *Eucalyptus grandis* hybrid in different tree planting spacings.

MATERIAL AND METHODS

Study area

The study was conducted in a stand composed of *Eucalyptus urophylla* x *Eucalyptus grandis* hybrid (Clone GG 100) in a small rural property in the municipality of Lamim, located within the Zona da Mata area in the state of Minas Gerais (20°47'S, 43°28'W). The municipality is located at an average altitude of 779 m, presenting annual accumulated rainfall of 1,549 mm and an average annual temperature of 19.3 °C, with the coldest period occurring from April to October. According to Köppen's classification, region's climate is Cwb, which is defined as subtropical of altitude, characterized by dry winters and temperate summers (Alvares et al., 2013). The region is predominantly composed of mountainous terrain, with slopes embedded in flat-bottomed valleys formed by terraces and larger riverbeds. The predominant soils in the region are classified as Dystrophic Red-Yellow Latosol (Coelho et al., 2008).

Planting was conducted in December 2011. The site preparation consisted of controlling leaf-cutting ants with granulated baits, mowing, total area desiccation, demarcation, and manual opening of planting holes (approximately 0.3 × 0.3 × 0.3 m), using the 2×1, 2×2, 3×2 and 3×3 m spacings. Fertilization at planting was performed by applying 200 g of reactive rock phosphate at the bottom of the planting hole, and 150 g of other fertilizers post-planting, including simple superphosphate in lateral holes (10 days post-planting), NPK (20-00-20), 0.5% B, and Zn (40-60 days post-planting), as well as potassium chloride and 1% B (two rainy seasons post-planting).

The model $Ln(Ht) = \beta_0 + \beta_1 / dbh + \varepsilon$ was adjusted for each spacing and age to a total of 12 hypsometric equations used to estimate the heights of the trees in the plots, where *Ht* is the total height (m), and *dbh* is the diameter at breast height (i.e. 1.30 m) (Gomes et al., 2022). The Smalian method was used to determine the observed volume of trees.

Wood properties

At 84 months after planting, five trees with an average diameter were selected in each spacing. Sampling consisted of removing wood discs, approximately 5 cm thick, located at 0, 25, 50, 75, and 100% of the commercial height, with a minimum diameter of 6 cm. Initially, the percentage of heartwood and sapwood was determined by marking two perpendicular lines intersecting at the center of the pith. These measurements were performed with a 0.1 cm precision ruler. The distance from the edges to the beginning of the heartwood was measured, and consequently, the area of the heartwood itself. The sapwood was calculated as a function of the difference from the total area in all longitudinal positions.

The basic density of the wood was determined from base to top of the tree by using the water immersion method, following ASTM D 2395 (method B) (ASTM, 1998). The mean density of wood in the different spacings was obtained following Vital et al. (1984), in which the basic density of wood is calculated from the arithmetic mean of the opposite wedges removed along the trunk of the tree. Part of the remaining discs were sectioned and transformed into sawdust using the Willey mill, following the TAPPI 257 om-52 (TAPPI, 1998) standard, in order to be used for structural chemical composition analysis, immediate chemical composition analysis, higher heating value, and thermogravimetric analysis. Samples composed of all longitudinal positions were collected from part of the remaining disks in approximately 1×1×1 cm dimensions for the production of charcoal in a muffle furnace.

The structural chemical composition of the wood was determined by using the ground samples that passed through the 40-mesh sieve and were retained in the 60-mesh (ASTM, 1982). The absolute dry content of the wood was determinate following TAPPI 264 om-88 (TAPPI, 1996a). The extractives content of the wood was determined in duplicate following TAPPI 204 om-88 (TAPPI, 1996b). The insoluble lignin content was obtained by the Klason method in duplicates, modified following the procedure proposed by Gomide and Demuner (1986). Soluble lignin was determined by spectrometry, following Goldschimid (1971). The total lignin content was also obtained by summing the soluble and insoluble lignin values.

The ash, volatile materials, and fixed carbon content were obtained following ASTM D3174-04 and ASTM D3175-89 (ASTM, 1997; 2010). The higher heating value of wood was determined following ASTM D240-02 (ASTM, 2007) using an adiabatic bomb calorimeter. The DTG-60H (Shimadzu) apparatus was used to obtain the thermogravimetric curves (TGA). The analyses were performed in an open alumina capsule with an atmosphere containing nitrogen gas at a constant flow rate of 50 mL min^{-1}. The curves were obtained from 100 °C to a maximum temperature of 450 °C, with a heating rate of 10 °C min^{-1}. Moreover, the TGA were obtained for differential thermal analysis (DrTGA).

Carbonization and charcoal properties

The carbonization was performed with samples of absolutely dry wood from each disc along the commercial height, comprising a composite sample of all longitudinal positions with approximate final dimensions of 1×1×1 cm. In total, three carbonizations were conducted per treatment, except for the 2×1m treatment, which was subjected to two carbonizations due to the lower availability of material. The carbonizations were performed in an electric muffle furnace adapted with a gas recovery system at a heating rate of 1.67 °C min^{-1}, with an initial temperature of 150 °C and final temperature of 450 °C. The entire process lasted for 4.5 h.

The gravimetric yield and friability of charcoal were determined; the latter aimed to verify the content of fines when subjected to breakage, abrasion, or rupture (ASTM, 1997). For this purpose, approximately 20 g of charcoal were weighed using a friabilometer equipment (MA 791) at 35.5 rpm for 14 min. After this time, the samples were collected, classified in a 9.5 mesh sieve and the percentage of fines were determined (Gomes and Oliveira, 1980). The apparent relative density was determined following the methodology proposed by Vital et al. (1984), which refers to a hydrostatic method in which mercury immersion is used. Bulk density was determined by the ratio between the mass of charcoal contained in a 40×40×40 cm box with internal dimensions. The charcoal samples were arranged up to the upper level of the box, with two repetitions being performed for each sample. Subsequently, the box was weighed on an analytical scale and its values were calculated following Brito et al. (1982). The ash content, volatile matter, and percentage of fixed carbon were obtained following ASTM D3174-04 and ASTM D3175-89 (ASTM, 1997; 2010). Figure 1 presents a summary flowchart of the methodology used in the analysis of wood and charcoal, along with the mass estimates.

Mass and energy estimates

Dry wood mass was obtained by multiplying the mean annual increment at 84 months by the basic density of the wood, as described in equation (1). Subsequently, lignin mass in equation (2), charcoal mass in equation (3), and energy per hectare in equation (4) were calculated. where: DWM = dry wood mass (t); MAI = mean annual increment (m^{3}ha^{-1}.year^{-1}); BD = basic density (t.m^{-3}); LM = lignin mass (t); LT = Total Lignin (%) /100; CM = mass of charcoal (t); GY = gravimetric yield (%) /100; Energy = energy per hectare (MJ.ha^{-1}.year^{-1}); HHV = high heating value (MJ.kg^{-1}).

$$DWM = MAI \times BD \quad (1)$$

$$LM = DWM \times LT \quad (2)$$

$$CM = DWM \times GY \quad (3)$$

$$Energy = DWM \times HHV \quad (4)$$

Statistical analysis

The experiment was performed using four treatments (spacings). For the analysis of wood quality, five replications were used (sample trees). For the charcoal analysis, three replications were used for the 2×2, 3×2 and 3×3 m spacings and two replications were used for the 2×1 m spacing. The difference in number of replications between spacing treatments was due to differences in the diameter of trees and the amount of material produced by carbonization.

The data related to wood, charcoal, and estimates of mass and energy per hectare were subjected to t test ($p < 0,05$) for comparison of means by using the Statistica® v. 13 (2018) software program. Principal component analyses were performed to evaluate the relationships between wood and charcoal variables as a function of spacing. Initially, the data were processed and the original variables were normalized. Normalization was achieved by transforming each new data value as $zi = \left(xi - \overline{x}\right) / s$, where zi is the new data value, xi is its original value, $\overline{x}$ is the sample mean, and s is the standard deviation. As a result, the mean and standard deviation become zero and one, respectively. Subsequently, biplot-type plots were produced by the selection of the first two principal components.

By applying the wood and charcoal variables to the principal component, the relative contributions of each variable were identified. Individual contributions were calculated by the ratio between the correlation of each variable in the principal component analysis and the sum of the absolute correlation coefficients.

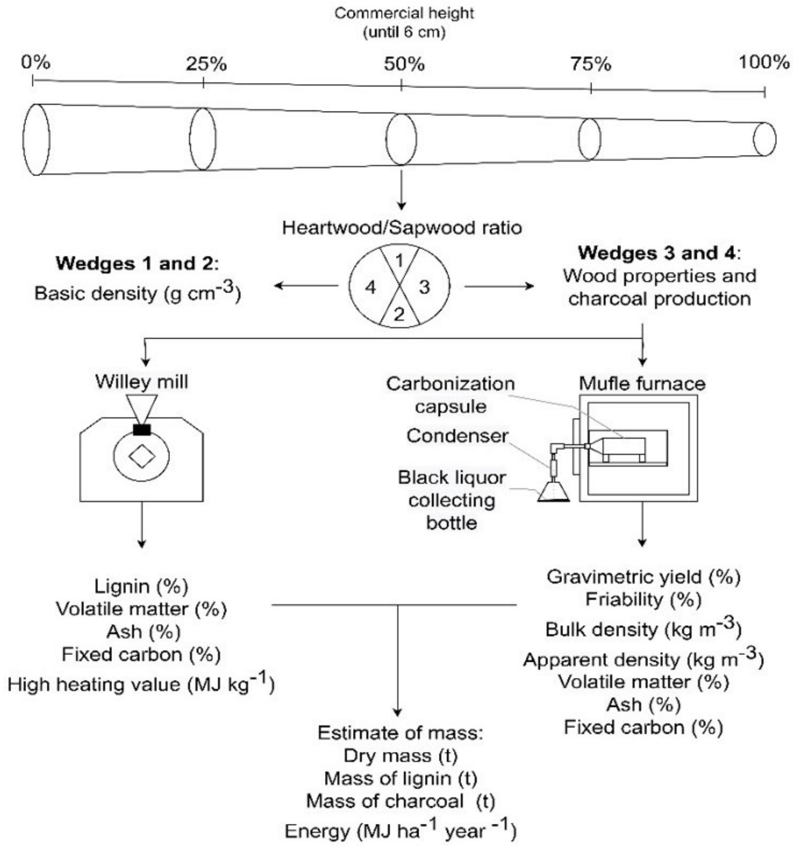

Figure 1: Flowchart of the methodology used in the analysis of wood and charcoal.

RESULTS

The heartwood/sapwood ratio, volatile matter, and fixed carbon content, as well as the higher heating value of wood were not influenced by planting spacing (Table 1). The basic density of wood in the 3×3 m spacing differed significantly from the others. The ash content for the reduced spacings (2×1 and 2×2 m) was statistically similar, while the percentages for the 3×2 and 3×3 m spacings differed from each other. The lowest total lignin content was observed in the smallest planting spacings (Table 1).

The apparent relative density of charcoal was not influenced by spacing (Table 2). Differences between wide (3×2 and 3×3 m) and narrow (2×1 and 2×2 m) spacings were found in relation to volatile matter, ash, and fixed carbon contents, as well as gravimetric yield. Lower friability averages were observed from wood coming from the 3×2 m spacing treatment (Table 2).

A wood mass loss of 16.75% was observed for the temperature range of 200-300°C. Moreover, the temperature range of 300 and 400 °C presented an average loss of 56.5%. The average residual mass was 26.75%, with the highest values observed for the 2×2 and 3×3 m spacings (Table 3).

The thermal degradation profiles of wood as a function of spacing are presented in Figure 2. Thermogravimetric curves (TGA) show the loss of mass as a function of temperature while its derivative (DrTGA) represents the variation of mass over time. It can be noted that the profiles are similar, with few modifications for the different spacings (Figure 1).

The degradation profiles suggest that three degradation ranges exist. The first range is up to temperatures close to 100 °C, where wood drying occurs; however, it should be noted that this study observed no water loss since the wood was dried to 0% moisture. The second range is from 225 to 275 °C, where hemicelluloses degradation happens. Lastly, the third range is from 325 to 375 °C where cellulose decomposition occurs. Lignin degradation starts at relatively low temperatures, but with a low rate of decomposition, with significant degradation being observed only above 450 °C (Pereira et al., 2013a).

The dry wood mass produced in the 2×2 m spacing showed statistically higher values than other spacings due to its higher average annual increment (59.9 $m^3 ha^{-1} year^{1}$). The 2×1 m spacing showed lower values of dry wood mass, despite presenting a basic wood density equivalent to that found in the 2×2 m spacing. The values observed in the 3×2 and 3×3 m spacings were statistically equivalent (Figure 3).

Table 1: Wood properties of the *E. urophylla* x *E. grandis* hybrid in different planting spacings.

Variable	Comparisons	Mean 1	Mean 2	t test value	p-value
H/S	2×1 - 2×2	1.05	1.05	-0.0062	0.995202
	2×1 - 3×2	1.05	1.08	-0.1272	0.901892
	2×1 - 3×3	1.05	1.04	0.0460	0.964413
	2×2 - 3×2	1.05	1.08	-0.1638	0.873985
	2×2 - 3×3	1.05	1.04	0.0661	0.948919
	3×2 - 3×3	1.08	1.04	0.2073	0.840938
BD	2×1 - 2×2	0.45	0.45	-0.2004	0.846189
	2×1 - 3×2	0.45	0.47	-1.8704	0.098339*
	2×1 - 3×3	0.45	0.51	-4.3351	0.002495*
	2×2 - 3×2	0.45	0.47	-2.3012	0.050377*
	2×2 - 3×3	0.45	0.51	-5.1862	0.000836*
	3×2 - 3×3	0.47	0.51	-3.0201	0.016557*
LT	2×1 - 2×2	28.45	28.29	0.5317	0.623076
	2×1 - 3×2	28.45	30.54	-5.8828	0.004173*
	2×1 - 3×3	28.45	29.87	-4.0162	0.015914*
	2×2 - 3×2	28.29	30.54	-11.5310	0.000323*
	2×2 - 3×3	28.29	29.87	-8.1765	0.001218*
	3×2 - 3×3	30.54	29.87	2.4770	0.068432
VMC	2×1 - 2×2	85.83	86.29	-0.9734	0.358844
	2×1 - 3×2	85.83	85.53	0.8040	0.444623
	2×1 - 3×3	85.83	85.71	0.2154	0.834823
	2×2 - 3×2	86.29	85.53	1.9676	0.084656
	2×2 - 3×3	86.29	85.71	1.0349	0.330979
	3×2 - 3×3	85.53	85.71	-0.3873	0.708669
AC	2×1 - 2×2	0.48	0.41	1.9378	0.088641
	2×1 - 3×2	0.48	0.34	3.3254	0.010456*
	2×1 - 3×3	0.48	0.24	6.5585	0.000177*
	2×2 - 3×2	0.41	0.34	2.9339	0.018885*
	2×2 - 3×3	0.41	0.24	16.7604	0.000000*
	3×2 - 3×3	0.34	0.24	3.9416	0.004286*
FCC	2×1 - 2×2	13.69	13.30	0.8357	0.427551
	2×1 - 3×2	13.69	14.13	-1.1687	0.276173
	2×1 - 3×3	13.69	13.84	-0.2784	0.787745
	2×2 - 3×2	13.30	14.13	-2.1609	0.062701
	2×2 - 3×3	13.30	13.84	-0.9644	0.363096
	3×2 - 3×3	14.13	13.84	0.5815	0.576916
HHV	2×1 - 2×2	19.54	19.53	0.0932	0.928038
	2×1 - 3×2	19.54	19.41	1.2064	0.262139
	2×1 - 3×3	19.54	19.51	0.3369	0.744835
	2×2 - 3×2	19.53	19.41	1.0691	0.316239
	2×2 - 3×3	19.53	19.51	0.2019	0.845042
	3×2 - 3×3	19.41	19.51	-1.3687	0.208279

*Significant at 5% from t test; H/S: Heart/Sapwood ratio; BD: basic density ($g.cm^{-3}$); LT: total lignin (%); VMC, AC and FCC: volatile matter content, ash content, and fixed carbon content (%), respectively; HHV: high heating value ($MJ.kg^{-1}$).

Table 2: Gravimetric yield and charcoal properties of *E. urophylla* x *E. grandis* hybrid in different planting spacings.

Variable	Comparisons	Mean 1	Mean 2	t test value	*p*-value
GY	2×1 - 2×2	35.29	35.17	0.4238	0.700281
	2×1 - 3×2	35.29	36.62	-4.4451	0.021177*
	2×1 - 3×3	35.29	36.32	-2.8828	0.063383
	2×2 - 3×2	35.17	36.62	-15.3919	0.000104*
	2×2 - 3×3	35.17	36.32	-6.4003	0.003060*
	3×2 - 3×3	36.62	36.32	1.4929	0.209756
FRIAB	2×1 - 2×2	7.56	6.82	1.6738	0.192772
	2×1 - 3×2	7.56	6.12	3.4940	0.039652*
	2×1 - 3×3	7.56	6.52	1.4350	0.246768
	2×2 - 3×2	6.82	6.12	1.5465	0.196895
	2×2 - 3×3	6.82	6.52	0.4669	0.664892
	3×2 - 3×3	6.12	6.52	-0.6234	0.566787
BD_c	2×1 - 2×2	169.28	173.37	-0.8435	0.460909
	2×1 - 3×2	169.28	180.50	-1.8923	0.154798
	2×1 - 3×3	169.28	198.09	-4.4408	0.021232*
	2×2 - 3×2	173.37	180.50	-2.1713	0.095672
	2×2 - 3×3	173.37	198.09	-6.3969	0.003066*
	3×2 - 3×3	180.50	198.09	-3.7584	0.019803*
ARD	2×1 - 2×2	275.24	285.22	-0.5224	0.637534
	2×1 - 3×2	275.24	288.58	-0.6134	0.583012
	2×1 - 3×3	275.24	295.25	-0.9972	0.392154
	2×2 - 3×2	285.22	288.58	-0.2129	0.841833
	2×2 - 3×3	285.22	295.25	-0.6973	0.524019
	3×2 - 3×3	288.58	295.25	-0.4046	0.706505
VMC_c	2×1 - 2×2	32.09	30.51	1.7686	0.175113
	2×1 - 3×2	32.09	33.72	-3.7699	0.032669*
	2×1 - 3×3	32.09	33.86	-3.4679	0.040409*
	2×2 - 3×2	30.51	33.72	-5.0535	0.007213*
	2×2 - 3×3	30.51	33.86	-5.0067	0.007455*
	3×2 - 3×3	33.72	33.86	-0.4932	0.647729
AC_c	2×1 - 2×2	1.11	1.03	1.5043	0.229544
	2×1 - 3×2	1.11	0.75	5.4624	0.012057*
	2×1 - 3×3	1.11	0.68	7.0556	0.005852*
	2×2 - 3×2	1.03	0.75	7.6894	0.001539*
	2×2 - 3×3	1.03	0.68	11.1433	0.000369*
	3×2 - 3×3	0.75	0.68	1.6924	0.165825
FCC_c	2×1 - 2×2	66.80	68.46	-1.8325	0.164267
	2×1 - 3×2	66.80	65.53	2.5730	0.082279
	2×1 - 3×3	66.80	65.46	2.3454	0.100728
	2×2 - 3×2	68.46	65.53	4.6287	0.009817*
	2×2 - 3×3	68.46	65.46	4.4700	0.011075*
	3×2 - 3×3	65.53	65.46	0.1950	0.854880

*Significant at 5% from t test; GY: gravimetric yield (%); FRIAB: friability (%); BD_c and ARD: bulk and apparent relative density in (kg.m^{-3}); VMC_c, AC_c, and FCC_c: volatile matter content, ash content, and fixed carbon content (%), respectively.

Table 3: Wood mass loss (%) as a function of spacing and temperature ranges.

Spacing (m)	Temperature range (°C)			Residual mass
	100-200	200-300	300-400	
2×1	0	18	57	25
2×2	0	17	55	28
3×2	0	17	57	26
3×3	0	15	57	28
Mean	0	16.75	56.50	26.75

The 2×2 m spacing also showed a similar trend of higher values for total lignin mass, which can be attributed to its higher dry wood mass production. This is an important characteristic that supports the estimates of charcoal mass per hectare, which shows that the 2×2 m spacing was statistically superior, with a production of 9.6 t ha^{-1} $year^{-1}$ (Figure 3). Upon analyzing charcoal mass each spacing, significant differences were observed. This finding is related to the fact that the differences in the dry wood mass observed led to differences in the mass of charcoal per hectare, despite the spacings 3×2 m and 3×3 m presenting higher gravimetric yields in charcoal than those observed in the 2×1 m and 2×2 m. Moreover, by analyzing stored energy, the 2×2 m spacing was found to present a greater amount of energy, which is associated with the greater dry wood mass produced in that spacing (Figure 3).

Figure 4 displays the PCA scores from the variables related to wood and charcoal across the different spacings. The figure highlights the dissimilarities between treatments, which exhibit variations in the chemical and productive characteristics of both wood and charcoal. The spacing PCA scores reveal the formation of two distinct groups: one consisting of the narrower spacings (2×1 and 2×2 m) and the other comprising the wider spacings (3×2 and 3×3 m).

For wood, principal component 1 (PCA1) and 2 (PCA2) represent 70.7% and 23.8% of the total variation, respectively, which together explain 94.5% of the variations related to wood characteristics produced in the different spacings (Neisse et al., 2018). The narrower spacings (2×1 m and 2×2 m) presented scores located close to the vectors of the HHV and VMC variables. Conversely, the wider spacing scores (3×2 m and 3×3 m) were more associated with the BD, LT, FCC, and H/S variables of the wood, showing, in general, the highest values of FCC and LT, and the lowest values of AC and VMC. This trend was also observed when comparing the means using the t test.

The highest relative contributions to wood were LT and FCC, both with 22%, followed by the HHV (20%) and VMC (21%). The least representative variable was basic density, with a 5% relative contribution. This indicates that the variables LT and FCC are the ones that most contribute to the differentiation of spacings, expressing greater variations. For charcoal, PCA1 and PCA2 capture 76.8% and 15.4% of the data variation, respectively. Furthermore, it can be seen that the spacings 2×1 and 2×2 m were associated with FCC_c and FRIAB variables, whereas the spacings 3×2 and 3×3 m presented a positive relationship with VMC_c, GY, BD_c, and ARD.

The highest relative contributions for charcoal are, in order of importance, GY > VMC_c > FCC_c ≥ BD_c ≥ ARD > FRIAB. This analysis indicates that gravimetric yield and volatile matter contribute to differentiation among spacings. This trend is also indicated by the results from the t test. In general, the same results are observed when comparing the t test and multivariate analysis. This demonstrates that, for a high number of variables, multivariate analysis becomes strategic since it can show trends and relative contributions.

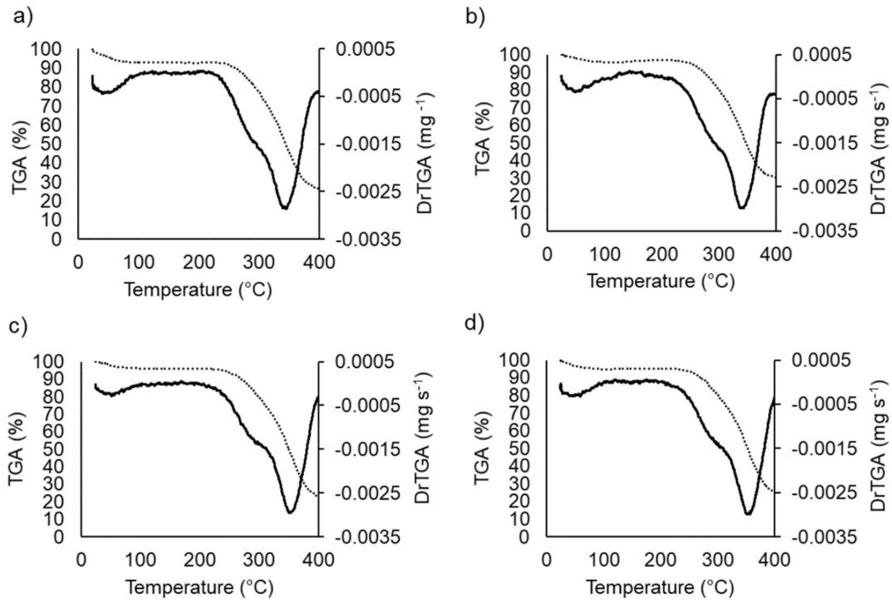

Figure 2: Wood degradation profiles of the *E. urophylla* x *E. grandis* hybrid in 2×1 m (a), 2×2 m (b), 3×2 m (c), and 3×3 m (d) planting spacings. Solid and dashed black lines represent TGA and DrTGA, respectively.

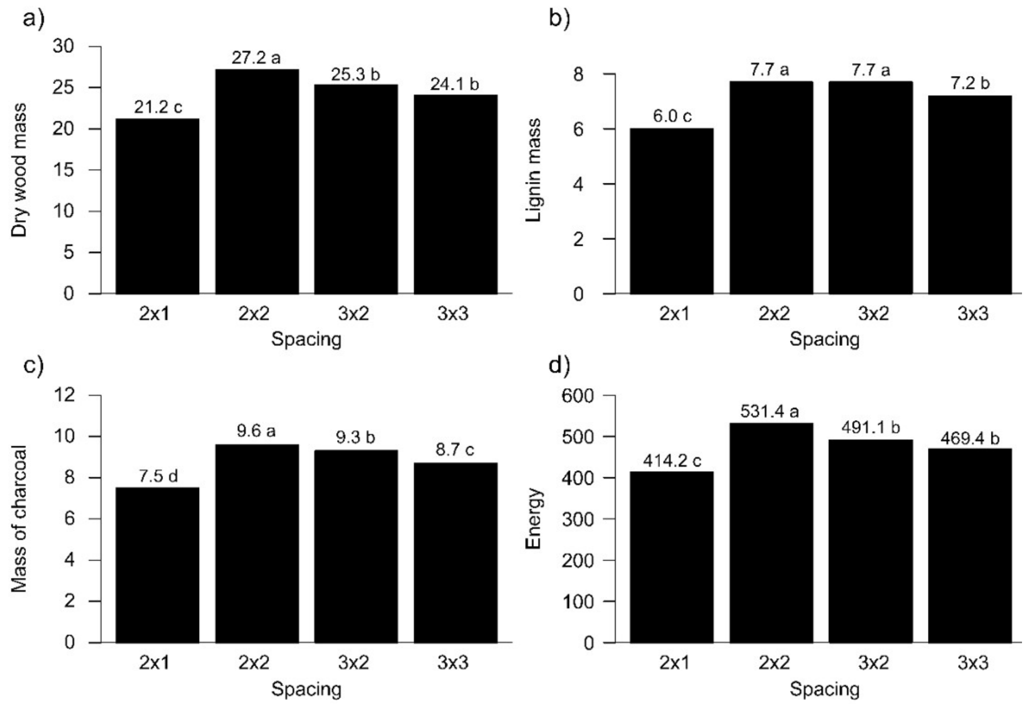

Figure 3: Averages of dry wood mass (t.ha^{-1}.year^{-1}), lignin mass (t.ha^{-1}.year^{-1}), mass of charcoal (t.ha^{-1}.year^{-1}), and energy (MJ.ha^{-1}.year^{-1}) in different planting spacings of the *E. urophylla* x *E. grandis* hybrid (t test, α = 5%).

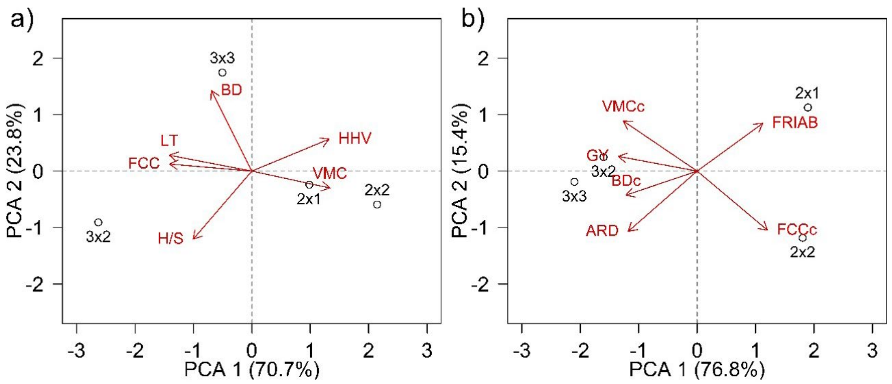

Figure 4: PCA scores and the relative contribution of wood (A) and charcoal (B) variables for the *E. urophylla x E. grandis* hybrid in different planting spacings. where: H/S: Heart/Sapwood ratio; BD: basic density (g.cm^{-3}); LT: total lignin (%); VMC, AC and FCC: volatile matter content, ash content, and fixed carbon content (%), respectively; HHV: high heating value (MJ.kg^{-1}); GY: gravimetric yield (%); FRIAB: friability (%); BD_c and ARD: bulk and apparent relative density (kg.m^{-3}); VMC_c, AC_c, and FCC_c: volatile matter content, ash content, and fixed carbon content (%), respectively.

DISCUSSION

Wood

Spacing did not influence the H/S ratio, which is similar to the results observed by Brito et al. (2019), who evaluated different planting spacings (3×1, 3×2, 3×3 and 3×4 m) of *E. grandis x E. urophylla* at 48 months of age. In general, spacings that promote diameter growth tend to generate more brittle charcoal, producing more fines during transport and handling (Pereira et al., 2016; Carneiro et al., 2016). However, in this study, the influence of spacing on brittle charcoal was not observed, which may be explained by the size of the wood piece used in the carbonization process.

Basic density was influenced by spacing, being higher when the area per plant was greater. This is justified by the environment where the hybrid is planted since this variable presents a strong relationship with the available growth resources (Kunstler et al., 2016; Clough et al., 2017;

Ibanez et al., 2017). Furthermore, Almeida et al. (2020) have reported that basic density is a characteristic with high heritability and undergoes modifications from the environment where the tree is planted.

In drier regions with low rainfall, higher wood basic densities are often observed associated with lower trunk biomass volumes, whereas in more humid areas these relationships are more associated with the genotype x environment interactions (Rocha et al., 2020). This corroborates the results found in this study since the average annual increment in the 3×3 m spacing at 84 months of the *E. urophylla x E. grandis* hybrid was the smallest among the analyzed spacings, providing greater basic density per plant. Meanwhile, the 2×1, 2×2, and 3×2 m spacings provided the highest MAI and lowest basic densities per plant. Therefore, it can be inferred that environments that promote faster growth, that is, a higher growth rate, generally present lower wood basic densities (Rigatto et al., 2004; Moulin et al., 2017).

Lignin shows a chemical composition with structures with high levels of aromaticity, along with different sizes and forms of arrangement, which promotes greater resistance to thermal degradation when compared to cellulose and hemicellulose (Haykiri-Acma et al., 2010; Xiao et al., 2020). Industries in the energy sector aim for a minimum percentage of 28% lignin content for wood (Pereira et al., 2013b). Protásio et al. (2014), Santos et al. (2011), and Arantes et al. (2011) found mean values of 32%, 29.75%, and 31.05%, respectively, for lignin content in *Eucalyptus spp.* clones. Therefore, the values found in this study are consistent with those observed in the literature.

Spacings did not influence the contents of volatile matter and fixed carbon in the wood but affected the ash content. In the narrower spacings, a greater competition for growth resources occurs, which favors the development of roots, mainly fine ones, for exploration and extraction of nutrients, generating a higher ash content (Vital et al., 2013; Craine et al., 2013). Similar results were found by Eufrásio Júnior et al. (2018) when studying a clone of *E. urophylla* x *E. grandis* at 24 months in the planting spacings of 2.8×0.5 and 2.8×1.5 m.

The high heating value is an excellent parameter to assess the quality of wood for energy use (Brand et al., 2015). In this study, spacing did not influence the heating value of the wood, which presented an average value of 19.49 MJ kg^{-1}. One of the explanations is related to the fact that the calorific value is a genetic characteristic, with small variations within the genus, and is not influenced by planting spacing (Santos et al., 2012).

Regardless of spacing, the mass loss of wood as a function of temperature agrees with the values observed for the *Eucalyptus* genus. Santos et al. (2012) and Pereira et al. (2013a) found mass losses of 46.4% and 52%, respectively, in temperature range of 300 to 400 °C. Fialho et al. (2019) observed that the greatest mass losses occurred in the temperature range of 300 to 450 °C. This range is associated with the greatest correlations between wood and charcoal properties, which can be explained by the degradation of hemicelluloses and cellulose.

Despite similar losses between spacings in the temperature range of 300 to 400 ºC, with averages close to 57%, the residual mass was higher for the wider spacings, ranging from 25% in the 2×1 m spacing to 28% at 3×3 m spacing, resulting in a 12% increase. This finding is primarily due to the higher levels of lignin and basic density, which are associated with greater energy potential and resistance to thermal degradation (Pereira et al., 2013b).

Charcoal

Gravimetric yields in charcoal were 36.6% and 36.3% for the 3×2 and 3×3 m spacings, respectively. This can be explained by the complex structure of lignin present in wood and its greater resistance to thermal degradation (Pereira et al., 2013a). Furthermore, Haykiri-Acma et al. (2010) mention that lignin is one of the most important components to produce charcoal due to its high levels of aromaticity, size, and arrangement of structures.

One solution to overcome the low levels of fixed carbon is to increase carbonization time. Soares et al. (2015) reported that the highest charcoal yields were found in genetic materials aged seven years, and this superiority may be related to the chemical characteristics and size of the carbonized material. Trugilho et al. (2019), in a study evaluating the effects of the diameter of eucalyptus wood, found that the largest diameter classes presented, in general, higher yields of charcoal, which is probably associated with the lignification of parenchyma cells and greater presence of substances such as aromatic compounds and tannins. The results of the present study also corroborate those found by Reis et al. (2012), Santos et al. (2012), and Briseño-Uribe et al. (2015).

Spacing significantly influenced charcoal friability. It was noticed that the charcoal produced from wood from the 3×2 m spacing generated more fines, with contents above 6.0%. Wider spacings such as 3×2 m result in trees of larger diameter, which is related to increased impermeability in the heartwood. Since higher heartwood impermeability is associated with higher internal pressures in the wood cells during the process of carbonization, wider spacings have also been found to result in greater number of fines (Silva et al., 2019).

The charcoal produced from wood collected in the 3×3 m spacing presented higher bulk density compared to charcoal from the others spacings. This finding might be associated with the higher basic wood density found in the 3×3 m spacing, which was also higher than in all other spacings. No statistical differences were observed for the apparent relative density as a function of spacing, which averaged 286.0 kg m^{-3} across all spacings.

Fixed carbon contents in charcoal ranged from 65.46 to 68.46% across spacings. Such values are below those found by Soares et al. (2014), in which they used the same carbonization rate and found values of 76.85% and 22.82% for fixed carbon and volatile material contents, respectively. In general, the average values were lower than desired for the energy sector since this difference can be explained by the negative relationship between fixed carbon and volatile material content, which reached averages of 32.55% and, consequently, lower fixed carbon contents (Silva et al., 2018).

Wider spacings are usually associated with trees of greater diameter and total heights, along with higher basic densities and total lignin contents. Therefore, denser woods are less degradable during carbonization, which leads to lower levels of fixed carbon and, consequently, higher percentages of volatile matter (Jesus et al., 2017).

The highest ash content was observed in charcoal produced from wood obtained from the denser spacings. This variation occurred due to the high rate of intra-specific competition in these spacings, which promotes thinner trees, lower growth rates, and possibly higher percentages of sapwood. Despite significant differences in ash content between spacings, it should be noted that the ash contents found in this study agree with Carneiro et al. (2016) and Santos et al. (2016), with percentages lower than 1%.

Mass estimates

Narrower spacings tend to result in more dry wood mass per hectare compared to wider spacings. This is due to the direct relationship between volumetric production and greater density of plants per area, which reflects on a greater amount of dry matter. These results are supported by Santos et al. (2012), Caron et al. (2015), and Saraiva et. (2017), who studied different species of *Eucalyptus* and planting spacings.

When choosing the spacing for eucalyptus stands to be used for energy purposes, particular attention should be given to the wood properties, especially basic density, and lignin content, as these will have direct influence on the production of dry mass of wood and charcoal yield (Rocha et al., 2015). Higher planting densities lead to increased volumetric yield and greater amounts of dry wood mass per hectare despite resulting in the lowest basic densities, total lignin contents in wood, and gravimetric yield.

The 2×2 m spacing showed the highest estimates of lignin and gravimetric yield, which can be an alternative for producers aiming to combine high productivity with good quality of the raw material. This spacing also resulted greater generation of energy, which can be attributed to its high production of biomass volume and not its heating values no differences between heating values were found between spacings. This finding agrees with Torres et al. (2016), who observed higher values of stored energy per hectare in smaller spacings (9×1 m).

Multivariate analysis

Multivariate analysis has been applied in forestry with the aim of identifying the most relevant wood properties and dendrometric characteristics for charcoal production (Beltrame et al., 2012; Figueiró et al., 2019). However, this technique is still underutilized for spacing. This study shows that principal component analysis can assist in decision-making by allowing the evaluation of the characteristics of wood and charcoal associated with planting spacing.

This study showed dissimilarity between spacing treatments for the analyzed conditions. Lignin content, fixed carbon, and volatile matter are important variables for assessing wood properties and together account for approximately 60% of the variation in the data. Previous studies, such as those by Castro et al. (2013) and Protásio et al. (2013), also applied principal component analysis and found that these characteristics were key in differentiating between treatments/spacings, explaining over 80% of the variance.

The variable with the highest relative contribution in the charcoal analysis was the gravimetric yield, which is desirable in the charcoal production process since it results in a greater use of wood in carbonization ovens and, consequently, higher energy output (Brand, 2010). The results of this study are consistent with those by Reis et al. (2012) and Dias et al. (2016), who analyzed different wood and charcoal properties.

CONCLUSION

Spacing between trees influenced wood quality indicators. The 2×2 m spacing showed higher estimates of mass and energy per hectare. However, wide spacings with an area greater than 6 m^2 are more suitable for charcoal production due to their superior wood properties, especially basic density and total lignin, which influence gravimetric yields and bulk density.

AUTHORSHIP CONTRIBUTION

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