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Original Article

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Influence of Wood Physical Properties on Charcoal from *Eucalyptus* spp.

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ABSTRACT

The use of wood in the form of charcoal for energy production, has great economic importance in Brazil. In this context, the study of variables and mechanisms that affect charcoal quality is essential. The present study aimed to verify the influence of some physical properties of *Eucalyptus* wood on the quality and yield of the produced bioreducer. We used three commercial *Eucalyptus* clones, cultivated for use in the steel industry, determining wood density and shrinkage, density and immediate chemistry of the charcoal produced and the charcoal gravimetric yield. The data was submitted to Pearson's correlation analysis. Correlations between wood density and apparent charcoal density as well as charcoal ash content were observed. All clones presented characteristics suitable for the production of charcoal for the steel industry, with emphasis on the hybrid *E. urophylla* x *E. grandis*.

Keywords: steel charcoal, *E. urophylla* x *E. grandis*, charcoal properties, wood density.

1. INTRODUCTION

In 2016, the use of wood in the domestic energy supply contributed 8.0% to the Brazilian energy matrix (Brasil, 2017), presenting high renewable and productive potential, with highly competitive costs in the national electric sector compared to hydroelectric and fuel oil plants (Vilela et al., 2014). In this context, the use of charcoal is highlighted due to the significant demand for this material in the Brazilian steel sector, where it is used as a bioreducer.

Brazil is a model country and the world leader in charcoal production and use as a bioreducer for iron ore in pig iron production (Morello, 2015). In 2015, annual charcoal production was 6.187 million tons (FAO, 2017), coming largely from carbonisation of forests planted with the genus *Eucalyptus*, which is widely used in Brazil given its high productivity and wide range of applications in forest based industries, as well as for decreasing pressure on native forests (Stanturf et al., 2013).

Scientific and technological changes have led to advances in the management and genetic improvement of this genera, resulting in increased forest productivity and gains in wood quality and homogeneity, transforming Brazil into the largest centre of forest production on the planet, with an average of 36 m^3 ha^{-1} $year^{-1}$ of eucalyptus forests planted (Colodette et al., 2014; IBÁ, 2016).

In addition to productivity, the differences in chemical, physical and morphological wood composition should also be considered for charcoal production, as they can affect the characteristics of the final product (Trugilho & Silva, 2001). The variability of charcoal characteristics, such as lignin content and its sirigil/guaiacyl relation, basic density, diameter of the piece used in the carbonisation process and initial humidity, modify charcoal quality and yield (Soares et al., 2014; Costa et al., 2014; Soares et al., 2015; Araújo et al., 2016).

A range of wood characteristics must be considered in the production of bioreducers. However, basic density is an essential criterion in tree selection, as it is directly proportional to charcoal density and solid gravimetric yield (Pereira et al., 2012; Moutinho et al., 2016). Among the desirable physical characteristics, the steel industry requires that the apparent density of charcoal be as high as possible (> 0.300 g cm^{-3}), and that it have high mechanical resistance and low humidity values. In terms of chemical characteristics, charcoal with a high lignin content and a low siringil/guaiacyl ratio, low ash content (< 1%), average volatile materials content (< 25%), high calorific value (> 7,500 kcal kg^{-1}) and high fixed carbon content (> 75%) (Trugilho et al., 2005; Pereira et al., 2012, 2013) is preferred. Understanding the direct influence of the properties of wood as a raw material, the investigation of correlations between the source material and the final product is crucial.

Due to the economic importance of charcoal as a bioreducer and aiming to provide additional information about different *Eucalyptus* hybrids used in the steel industry in Brazil, this study verified the influence of physical wood properties on the quality and yield of charcoal produced, indicating the most appropriate clones for the production of charcoal used in the steel industry.

2. MATERIAL AND METHODS

We collected trees of *Eucalyptus urophylla, Eucalyptus urophylla x Eucalyptus grandis* and *(E. camaldulensis x E. grandis) x Eucalyptus urophylla* from an approximately 6-year-old commercial plantation, located in the Alto do Jequitinhonha region in the state of Minas Gerais, 17º41'38"S and 42º31'07"O, at 1,070 m above sea level. The trees were produced through genetic improvement programs by steel companies. Average annual temperature in the region is 21ºC, with accumulated precipitation of 1,166 mm.

Three trees of each clone were randomly selected and cut in the field, and we collected discs with a thickness of 15 cm at 0, 25, 50, 75 and 100% of commercial height, apart from an extra disk at 1.30 m from ground height (DBH).

From each disk, we collected samples in marrow-bark direction (radial), as shown in Figure 1. The number of samples varied according to the diameter of each disk. On average, 27 samples per tree were used for analysis.

The samples (20 x 20 x 40 mm^3), obtained in tangential, radial and longitudinal directions, were immersed in water until saturated, using a vacuum recipient, and then kiln-dried until constant mass was achieved. For each sample, we determined the basic density and the linear and volumetric shrinkage, adapting the standard NBR 7190 (ABNT, 1997).

The anisotropy coefficient was calculated as the ratio between tangential and radial shrinkage.

The same samples used for the determination of physical wood properties, previously kiln-dried, were used for carbonisation to increase the reliability of the results. Carbonisations were conducted in an electric muffle furnace with a maximum carbonisation temperature of 400°C and an average heat rate of 1°C min^{-1}, remaining stable for a period of 60 minutes.

Gravimetric charcoal yield was determined relating the mass of charcoal produced with the mass of the dried wood samples (Equation 1):

$$GYC = \left(Cm / Dwm\right) * 100 \quad (1)$$

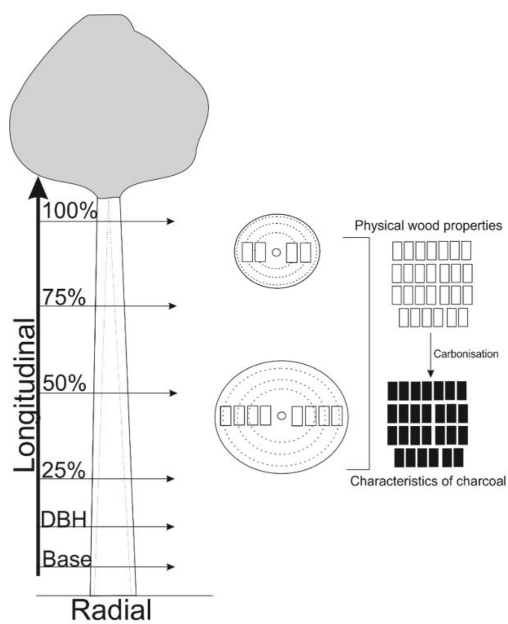

Figure 1. Longitudinal positions of wood discs and radial position of the samples.

where: GYC = gravimetric charcoal yield (%); Cm = charcoal mass; Dwm = dried mass of wood sample.

Apparent relative density (ARD) of charcoal was determined using dried charcoal mass and volume by immersion in mercury, according to the adaptation of the standard NBR 7190 (ABNT, 1997).

Chemical analysis of the charcoal produced was performed on carbonized samples, using six repetitions per tree (one for each longitudinal position). Volatile level (VL), ash content (AC) and fixed carbon content (FCC) in the dried base were determined according to the procedure established in the standard D1762-84 (ASTM, 2007).

To determine correlations between wood and charcoal density, we used a linear regression in a specific manner (for each treatment) and in a general way (without distinguishing between treatments). We determined the coefficient of Pearson's correlation ($p = 0.05$) to measure the association between the wood and charcoal variables, considering the data without distinguishing between treatments.

For all statistical analyses, we used the software package R, version 2.11.0 (R Development Core Team, 2011), and the *agricolae* package (Mendiburu, 2013). When differences were significant via variance analysis, we applied the Scott Knott test of multiple comparison at 5% probability.

3. RESULTS AND DISCUSSION

The basic density of the studied clones varied between 0.567 and 0.696 g cm^{-3}, with differences being statistically significant (Table 1). The values found by Pádua et al. (2015), when working with 5.5-year-old *Eucalyptus grandis x Eucalyptus urophylla*, are similar to those

Table 1. Average values of physical wood properties of the three tree clones used in this study.

Clone	Basic Density (g cm^{-3})	Shrinkage (%)				A.C.
		Tangential	Radial	Axial	Volumetric	
1. E. urophylla	0.658 b	6.821.3 b	4.84 b	0.04 b	12.17 b	1.45 b
Standard error	±0.014	±0.267	±0.217	±0.015	±0.439	±0.068
2. (*E. camaldulensis* x *E. grandis*) x *E. urophylla*	0.567 c	8.90 a	5.81 a	0.44 a	15.22 a	1.65 b
Standard error	±0.010	±0.547	±0.328	±0.152	±0.707	±0.133
3. E. urophylla x *E. grandis*	0.696± a	8.92± a	4.53 b	0.14 b	13.93 a	2.11 a
Standard error	±0.013	±0.556	±0.280	±0.050	±0.714	±0.157

A.C. = anisotropy coefficient. Averages followed by the same letter in the column did not differ significantly at 5% probability.

for *(E. camaldulensis x E. grandis) x Eucalyptus urophylla* clones, while Rosa et al. (2017), studying seven-year-old *Eucalyptus urophylla x Eucalyptus grandis* clones, found lower values (0.472 g cm^{-3}) compared to those in the present study.

In terms of wood shrinkage (Table 1), the values observed were comparable to those found by Gonçalves et al. (2009), who worked with 5.8-year-old progenies of *Eucalyptus,* but lower than those found by Oliveira et al. (2010), who found values of 15.3, 7.9 and 25.6% for tangential, radial and volumetric shrinkage, respectively, when studying 16-year-old *Eucalyptus urophylla* clones. The shrinkage values for *Eucalyptus* wood tended to increase according to the age of the material, due to the increase in density and thickness of the fibre wall and the content and composition of extractives (Hernandez 2007; Sette et al., 2012).

According to Oliveira et al. (2010), although volumetric shrinkage is important, what defines wood as an anisotropic material is the unequal dimensional shrinkage/swelling along the orthogonal axes, mainly tangential and radial, resulting in the anisotropy coefficient, which is the ratio between the values of the two plans. For charcoal production, the lower the wood coefficient, the lower the tendency towards defects and cracks during the drying step in the carbonisation process, which can positively affect the mechanical properties and the friability of the charcoal produced.

Therefore, considering the anisotropy coefficient values, the *(E. camaldulensis x E. grandis) x E. urophylla* clones presented lower values and did not differ significantly from each other, while the *E. urophylla x E. grandis* clone showed a significantly higher value.

Based on Pearson's correlation coefficients (Table 2), some physical wood properties showed significant correlations.

The higher values of tangential shrinkage lead to a higher anisotropy coefficient. According to Durlo & Marchiori (1992), this directly proportional relation can be explained by the higher concentration of cells with thick walls in the tangential plan, making the radial plan follow its dimensional movement. Consequently, the anisotropy coefficient, which is the result of this interaction, tends to increase.

Volumetric shrinkage can be conceptualised as the sum of linear shrinkages, which obviously results in a significant correlation between variables. Therefore, we did not apply the correlation test with these variables.

As for the significant correlation between basic density and volumetric shrinkage, it is important to mention that shrinkage is nothing more than the physical response of the wood to the chemical phenomenon of microfibrils approaching the S2 layer due to the impregnated water outlet. The amount of microfibrils increases with the density and thickness of the cell wall. The proportional increase of free hydroxyl groups increases the hygroscopicity of the wood, and consequently, its volumetric changes.

Based on our results (Table 1), the *E. urophylla* x *E. grandis* clone, which presented the highest density, also presented the highest volumetric shrinkage, corroborating with the correlation observed (Table 2). However, this was not observed for the (*E. camaldulensis* x *E. grandis*) x *E. urophylla* clone, which also showed a high volumetric shrinkage, albeit with a lower value of basic density between the three evaluated clones.

This asymmetric behaviour between clones corroborates the findings of Neves et al. (2011), which showed that basic density should not be evaluated in isolation. According to Pelozzi et al. (2012) the main component that influences these dimensional variations is the microfibril angle. In this context, future studies

Table 2. Pearson's correlation coefficients for physical properties of the evaluated clones.

Variable	Shrinkage				Basic Density	A.C.
	Tangential	Radial	Axial	Volumetric		
Tangential shrinkage	1					
Radial shrinkage	0.127	1				
Axial shrinkage	0.151	0.392*	1			
Volumetric shrinkage	----	----	----	1		
Basic density	-0.190	-0.161	-0.141	-0.249*	1	
Anisotropy coefficient	0.679*	-0.550*	-0.014	0.331*	-0.029	1

A.C. = anisotropy coefficient; *= significant at 5% probability.

should include the microfibril angle as a variable to be evaluated in the correlations, as the extractive content can also influence the sorption and dimensional movement of wood, conferring a higher hygroscopic stability on pieces due to the hydrophobic effect inside the cell walls, as shown by Hernandez (2007).

In terms of relative charcoal density, the *E. urophylla x E. grandis* clone differed significantly from the others (Table 3). The observed values for this variable for all clones were lower than the ones found by Trugilho et al. (2001), who worked with seven-year-old *Eucalyptus grandis* clones under similar carbonisation conditions and obtained a value of 0.44 g cm^{-3} for ARD, 36.8% for GYC and 79.5% for FCC. These values are higher than the ones found by Trugilho et al. (2005), who evaluated seven-year-old *Eucalyptus* hybrids, carbonised at 450°C, at a heat rate of 1.6ºC min^{-1}, and measured 0.31 g cm^{-3} for ARD, 40.2% for GYC and 67.97% for FCC.

In terms of charcoal gravimetric yield, the (*Eucalyptus camaldulensis* x *Eucalyptus grandis*) *x Eucalyptus urophylla* clone presented higher values, with significant differences (Table 3). However, it also showed a significantly lower density, while the ash content (AC) was significantly higher when compared to the other evaluated clones, which can compromise both usable volume inside the blast furnace and the quality of the steel produced.

The *E. urophylla* clone presented intermediate values for the variable apparent density, with significantly lower charcoal density and fixed carbon values when compared to the *E. urophylla x E. grandis* hybrid. Dias et al. (2016) found an apparent density value of 0.34 g cm^{-3} when working with *E. grandis* clones (final temperature 500ºC, with a heating rate of 1.67°C). The authors suggested that this variable can be affected both by the process and by the raw material.

The *E. urophylla x E. grandis* clone presented the second highest charcoal yield (GYC); it also had the highest density and fixed carbon values. These parameters, according to Souza et al. (2016), are indicators of the bioreducer production quality.

These values are higher than those found by Arantes et al. (2013), who worked with six-year-old *Eucalyptus grandis x Eucalyptus urophylla* clones of different diametric classes, carbonized at 450ºC of temperature with a heat rate of 1.6ºC min^{-1}; these authors obtained a charcoal yield of 34%. As the carbonisation parameters in our study differed in final temperature and heating rate of these authors, it is important to highlight that lower temperatures and heat rates, as observed in the present study, tend to increase both charcoal density and yield.

Basic wood density was positively and significantly correlated with apparent charcoal density (Table 4). This result is in agreement with the findings of Pereira et al. (2012), who studied different *Eucalyptus* clones and observed a direct influence of wood density on apparent charcoal density.

Pereira et al. (2012) states that although basic wood density is a quality index for wood, it cannot be used in isolation as a parameter to select clones for charcoal production. Gravimetric yield is an important parameter in charcoal production, however, it was not correlated with any of the wood variables. The increase of gravimetric yield depends on other factors, mainly the final temperature of the carbonisation process, and is also associated with higher lignin content and lower siringil/guaiacyl ratio of the wood (Gouvêa et al., 2015; Pereira et al., 2013).

Table 3. Gravimetric charcoal yield and charcoal properties of the three clones.

Clones	ARD (g cm^{-3})	GYC (%)	VL (%)	AC (%)	FCC (%)
1. E. urophylla	0.343 b	33.74 c	35.2 a	1.1 b	63.4 b
Standard error	±0.006	±0.253	±0.898	±0.241	±0.933
2. (*E. camaldulensis* x *E. grandis*) x *E. urophylla*	0.321 b	38.99 a	33.5 a	1.9 a	64.1 b
Standard error	±0.004	±0.300	±0.822	±0.259	±0.751
3. E. urophylla x *E. grandis*	0.371 a	35.68 b	29.7 b	1.1 b	69.2 a
Standard error	±0.008	±0.402	±1.301	±0.110	±1.260

ARD: apparent relative density; VL: volatile levels; AC: ash content; FCC: fixed carbon content; GYC: gravimetric yield in charcoal. Averages followed by the same letter in the same column did not differ significantly at 5% probability.

The charcoal characteristic which most correlated with the physical properties of evaluated clones was ash content (AC), according to Table 4. The significant correlation indicates that denser wood with a higher tangential and volumetric shrinkage, will produce charcoal with a lower ash content, which is an important variable when using this product as a bioreducer, because bioreducers are incorporated into metallic alloys which makes them brittle (Trugilho & Silva, 2001).

The results of the correlation analysis between basic wood density and apparent charcoal density for three *Eucalyptus* hybrids are presented in Figure 2.

Basic wood density can explain around 73% of the apparent density variation of charcoal, confirming

Table 4. Pearson's correlation coefficients for physical wood properties and charcoal characteristics evaluated in this experiment.

Variable		Basic density	Wood properties				
			Shrinkage				Anisotropy coefficient
			Tangential	Radial	Axial	Volumetric	
Charcoal characteristics	Apparent relative density	**0.545***	-0.336	0.223	-0.049	-0.200	-0.367
	Volatile levels	-0.341	-0.133	0.144	0.343	-0.035	-0.149
	Ash content	**-0.587***	**-0.636***	0.136	0.239	**-0.595***	-0.504
	Fixed carbon content	0.432	0.237	-0.164	-0.375	0.134	0.231
	Gravimetric charcoal yield	0.281	-0.100	0.459	-0.401	0.010	-0.332

*= significant at 5% probability.

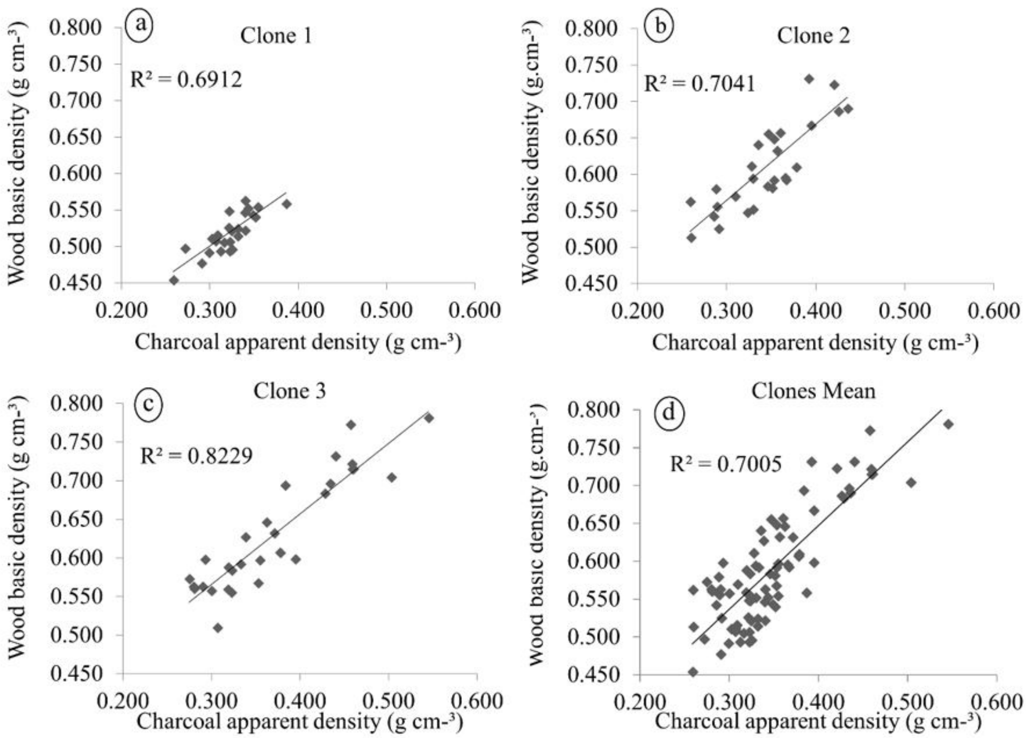

Figure 2. Relationship between basic wood density and the apparent density of charcoal from wood of *Eucalyptus urophylla* (a), *Eucalyptus urophylla x Eucalyptus grandis* (b) and *(Eucalyptus camaldulensis x Eucalyptus grandis) x Eucalyptus urophylla* (c) and averaged across the three clones (d).

the direct and positive ratio between these variables. For charcoal production, it is therefore advisable to select wood with a high basic density.

CONCLUSIONS

Basic wood density significantly influenced volumetric shrinkage of wood, the ash content and the apparent density of the charcoal.

All evaluated clones presented appropriate characteristics for the production of charcoal to be used in the steel industry, highlighting especially the *E. urophylla x E. grandis* hybrid.

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