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WOOD QUALITY OF FIVE *EUCALYPTUS* SPECIES PLANTED IN RIO GRANDE DO SUL, BRAZIL FOR CHARCOAL PRODUCTION

Simetti R[1, *], Bonduelle GM[2] & da Silva DA[2]

[1]*Universidade Federal de Lavras, 37200-000 Brazil*
[2]*Departamento de Engenharia e Tecnologia Florestal, Universidade Federal do Paraná, 80210-132 Brazil*

rodrigo.simetti@gmail.com

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The objective of this study was to evaluate the wood quality of *Eucalyptus benthamii, E. dunnii, E. grandis, E. saligna* and *E. urophylla* x *E. grandis* from seven-year-old commercial plantations in the state of Rio Grande do Sul for charcoal production. The wood properties determined for each species were basic density, structural chemical composition and high heating value. The materials was carbonised at 450 °C in a muffle furnace with a heating rate of 2 °C min^{-1}, from 100 °C up to 450 °C for 30 minutes. The yields of charcoal, pirolenous liquor and non-condensable gases were collected. Charcoal properties evaluated were fixed carbon, volatile and ash contents and high heating value. Yields of fixed and energy carbon were also calculated. A completely randomised design was used to evaluate the experiment. The results showed that all the species had similar charcoal quality, but differing in the structural chemical composition of the wood, resulting in differences in gravimetric yields. The species *E. benthamii* was superior compared to the others, thus, it is the most useful for charcoal production.

Keywords: Bioenergy, carbonisation, slow pyrolysis, wood science, wood density

INTRODUCTION

Brazil is the largest producer and consumer of charcoal in the world, mostly consumed by the steel and iron alloy industry. To meet the industrial demand for charcoal, high quality and fast growth materials are required, between five and seven years of cutting cycle. The genus *Eucalyptus* have been found suitable for such use, besides presenting great adaptation to different edaphoclimatic conditions (Couto & Müller 2013), making the genus interesting for application in Brazil where there is great climatic variability. In addition, Brazil stipulated a 2020 goal of using only planted forest plants for charcoal production, in order to reduce deforestation of the native forest and to have product uniformity, since planted forests provide homogeneous materials.

In Brazil, total *Eucalyptus* plantation area is 5.56 million hectares, with the largest planted areas in the states of Minas Gerais, São Paulo and Mato Grosso do Sul (IBÁ 2015). The most widespread species are *E. grandis*, *E. saligna*, *E. urophylla* and the hybrid *E. grandis x E. urophylla.* Several authors have related wood quality to charcoal quality, considering physical and chemical characteristics and their correlations (Oliveira et al. 2012, Protásio et al. 2013, Vale et al. 2010). Basic wood density is considered as one of the most fundamental characteristics for quality evaluation of the final product. The structural chemical composition of wood affects the yields of charcoal, pyroligneous liquor and non-condensable gases in the final product. Besides, the proximate chemical composition determines carbon and mineral availability, directly affecting the reduction process of metal alloys.

Therefore, it is necessary to know the wood quality and its correlations with charcoal, so that superior species and clones are selected for charcoal production. Thus, the objective of this study was to evaluate the wood quality of five *Eucalyptus* species and determine the relationship with charcoal production.

MATERIALS AND METHODS

Five different raw firewood were used for this study, *E. benthamii, E. dunnii, E. grandis, E. saligna* and a hybrid of *E. urophylla* x *E. grandis.* At the time of collection, the plants were seven years old and nine plants of each species were selected. Firewood comes from commercial plantations of Stora Enso Florestal, located in the state of Rio Grande do Sul in the municipalities of Alegrete and São Francisco de Assis. The climate of the region, according to the Koppen classification, is Cfah—subtropical mesothermic, constantly humid, with months of cold weather, frost from May to August, and intense heat predominant in January and February. The soil of the study area is classified as dystrophic red argisol. Table 1 shows the average planting data used.

Six discs, with approximately 10 cm height, were taken from the samples, base (10 cm of the soil), DHB (1.30 m of the soil), 25%, 50%, 75% and 100% with respect to the commercial height of the tree, considered up to the diameter of 6 cm with bark. After the collection, the discs were packed in plastic bags and sent for specimen preparation. Each disc was sectioned into four wedges from which one pair of opposing wedges was forwarded for the determination of basic density, from the other pair, a wedge was destined to specimen preparation for pyrolysis, and the remaining wedge was minced and milled in a Wiley mill. A sample consisting of the milled material of all sampled heights was prepared and sieved using 35- and 60-mesh sieves (Trugilho 2009). The fraction retained in the 60-mesh sieve was sent for determination of extractives, lignin, high heating value and proximate analysis.

In the determination of basic density, the precepts of standard NBR 11941 for hydrostatic balance were followed (ABNT 2003). For each height, the arithmetic mean of the two opposite wedges was considered, and for the tree, the arithmetic mean of all heights sampled was considered (Trugilho 2009).

For carbonisation, the wedge was transformed into chips (4 × 4 × 1 cm) and a sample consisting of all heights was oven dried at 103 ± 2 °C. After drying, the sample (100 g) was carbonised in a muffle furnace with a heating rate of 2 °C min^{-1}, from 100 °C to 450 °C for 30 minutes. The pyroligneous liquor was collected and non-condensable gases were released into the atmosphere. The charcoal and pyroligneous liquor yields were determined by the ratio of charcoal mass produced to dry wood mass at the beginning of the process. Non-condensable gases yield was calculated by the difference between wood mass and the yield of the above two. The apparent relative density of charcoal was determined in the same way as for basic wood density.

The standard NBR 14853 and 7989 was used to determine the extractive content and lignin content (Klason) of the wood (ABNT 2010 a,b). Holocellulose content was determined by the difference of the sum of the two above. The high heating value of wood and charcoal was determined according to standard NBR 8633, using an adiabatic calorimetric pump (ABNT 1984). Proximate chemical analysis was carried out in charcoal for the determination of volatile materials (VM), fixed carbon (FC) and ash (A), according to standard NBR 8112 (ABNT 1986).

The energy density of wood was calculated from the basic density and high heating value of wood, according to Equation 1, while the energy density of charcoal was calculated from the apparent relative density of charcoal and its high heating value, according to Equation 2.

$$ED_w = D_b * HHV_w \quad (1)$$

where, ED_w = energy density of wood (Gcal m^{-3}), DB = basic density of wood (kg m^{-3}) and HHV = high heating value of wood (kcal kg^{-1}).

$$ED_c = D_{ar} * HHV_c \quad (2)$$

Table 1 Dendrometric data

Material	Spacing (m)	DHB * (cm)	TH ** (m)	Origin
Eucalptus benthamii	3.5 × 2.0	16.50	29.80	Alegrete
Eucalptus dunnii	3.5 × 2.0	17.49	23.52	Alegrete
Eucalptus grandis	3.5 × 2.0	18.09	26.05	Alegrete
Eucalptus saligna	3.5 × 2.5	19.97	28.36	São Francisco de Assis
Eucalptus urograndis	3.5 × 2.5	18.69	30.11	Alegrete

*Diameter at 1.30 m from the soil, ** total height (SEFRGDS, 2014) where ED_C = energy density of charcoal (Gcal m^{-3}), D_{ra} = apparent relative density of charcoal (kg m^{-3}) and HHV = high heating value of charcoal (kcal kg^{-1}).

The fixed carbon yield and energy yield were also calculated, according to Equations 3 and 4, respectively, where the former represents the amount of fixed carbon retained in the final product and the latter represents the energy fraction of the wood retained in charcoal.

$$FCY = CY * FC \quad (3)$$

where FCY = fixed carbon yield (%), CY = charcoal yield (%) and FC = fixed carbon content of charcoal (%).

$$EY = CY * \frac{HHV_c}{HHV_w} \quad (4)$$

where EY = energy yield (%), CY = gravimetric yield in charcoal (%), HHVc and HHVw = high heating values of charcoal and wood, respectively.

For statistical analysis, a completely randomised design was used, having the species and nine replications (trees) as a variation factor. An analysis of variance was performed and the means were statistically compared by Tukey test at 5% probability when a significant difference was found. To perform the statistical analysis, the software R 3.1.2 was used (R CORE TEAM 2014).

RESULTS AND DISCUSSION

The species factor had a significant effect on all the properties evaluated in the chemical composition of wood, except for the high heating value of wood (Table 2). The results observed for high heating value were similar to those found by Eloy (2015), studying *E. grandis* in different spacings. Carneiro et al. (2014) studied *Eucalyptus sp.* clones and found HHV values between 4542 kcal kg^{-1} and 4633 kcal kg^{-1}. This variable is of interest for wood energy use, considering that it represents the amount of heat released during combustion (Santos 2010). It is observed that wood with higher holocellulose contents have a tendency to decrease charcoal yield (Protásio et al. 2012). This fact is associated with the lower thermal stability of hemicelluloses and cellulose in relation to lignin (Raad et al. 2006). Lower holocellulose contents are associated with a higher lignin content, since the former is calculated by the difference in relation to the latter (Vale et al. 2010, Costa et al. 2014).

The extractive contents and lignin values found in this study differed from those found by Costa et al. (2014) for hybrid *E. urograndis*, aged 3 to 7 years. The authors found extractive contents between 8 and 10%, and for lignin, lower than 22%. However, Oliveira et al. (2012) found a maximum extractive content of 2.29% and a lignin content of more than 30% for the same hybrid. Rocha et al. (2016) found higher lignin values, indicating possible influence of the spacing used. Regarding structural chemical composition, the five species presented a median potential as a bioreducer, showing lower lignin contents than those found in literature for ideal materials, however higher than 25%. The ash content of the studied wood was low, a characteristic desired for charcoal production, since it contributes to lower mineral content in the final product.

Table 3 shows the mean high heating value and proximate chemical composition of charcoal. A significant effect of species was observed for the contents of volatile materials and ash. The small variation between charcoal characteristics is related to the low influence of species over these properties and is explained by the fact that the

Table 2 Mean values of high heating value (HHV) and chemical composition of the evaluated wood

Species	HHV	EXT	LIG	HOLO	Ash
Eucalptus benthamii	4626 a	3.69 a	29.27 a	66.64 b	0.38 a
Eucalptus dunnii	4660 a	3.21 a	25.99 b	70.41 a	0.38 a
Eucalptus grandis	4532 a	1.20 b	26.60 ab	71.90 a	0.29 ab
Eucalptus saligna	4661 a	3.14 a	26.62 ab	79.95 a	0.27 b
Eucalptus urograndis	4585 a	1.27 b	26.16 b	72.21 a	0.34 ab

HHV = high heating value (kcal kg^{-1}), EXT = total extractive content (%), LIG = insoluble lignin content (%), HOLO = holocellulose content (%), Ash = ash content (%)

Table 3 Mean values of high heating value and proximate chemical composition of charcoal for the evaluated species

Species	HHV	FC	VM	Ash
Eucalptus benthamii	7603 a	77.80 a	21.15 ab	1.04 b
Eucalptus dunnii	7475 a	78.56 a	19.78 b	1.65 a
Eucalptus grandis	7505 a	76.59 a	22.21 a	1.19 ab
Eucalptus saligna	7395 a	75.95 a	23.21 a	0.83 b
Eucalptus urograndis	7490 a	78.06 a	20.92 ab	1.01 b

HHV = high heating value (kcal kg^{-1}), FC = fixed carbon content (%), VM = volatile materials content (%), Ash = ash content (%)

final carbonisation temperature was constant, which was also found by Protásio et al. (2013, 2014).

Mean contents of fixed carbon, higher than 75%, combined with low average ash contents (< 1%), qualify the charcoal produced from the five species as potential reducing agent in the steel sector (Protásio et al. 2014). The similarity between high heating value found for each plant species is related to the fixed carbon content, as these two characteristics are highly dependent on each other (Vale et al. 2010, Reis et al. 2012). The ash content of charcoal used in the steel industry can affect steel quality, resulting in cracks in metal alloys (Vital 2013).

The small variation between charcoal characteristics is related to the low influence of species over these properties, and the final carbonisation temperature was constant, as also found by Protásio et al. (2013, 2014). In a study with 7-year-old *E. urophylla*, Reis et al. (2012) found average ash contents of less than 0.81% and maximum content of volatile materials, 74.46%. Thus, in relation to proximate chemical composition and high heating value, it is suggested that charcoal of all species studied can be indicated for bioenergy and steel use.

Table 4 shows the values of wood basic density and apparent relative density of charcoal, as well as energy density of both materials. There was a significant difference in the four characteristics of the species. The species *E. dunnii* had the highest average value for basic wood density, resulting in higher energy density. For each species, the differences in density were the same as energy density. There was no significant difference in high heating values between the species. Energy density is a result of the product between basic wood density and its respective heating value. Therefore, it can be stated that basic wood density is an important tool for the selection of materials for energy purposes. The density of wood can be influenced by spacing and the age of planting (Pillai et al. 2013, Rocha et al. 2016, Pertiwi et al. 2017).

In relation to energy density of wood, the species *E. grandis* presented lower values than those reported in literature, even at lower ages. Protásio et al. (2013) found values between 2.16 and 2.38 Gcal m^{-3}, while Eloy (2015) found values in the range of 1.73 to 1.88 Gcal m^{-3}, similar to this study, but in younger material. The apparent relative density of charcoal was similar to basic wood density, as confirmed by Vale et al. (2010) and Protásio et al. (2013). A low reduction in charcoal density was observed for *E. benthamii*e and *E. dunnii* in wood, which may be related to the total extractive contents of these species (Costa et al. 2014).

Regarding gravimetric yields of the carbonisation process, a significant effect of species was observed in charcoal and pyroligneous liquor, while non-condensable gases did not show a significant effect (Figure 1). Higher yields in charcoal are better, as process yield increases, and the use of wood in charcoal kilns and the amount of final product is higher (Neves et al. 2011). According to Protásio et al. (2013), species with higher yields in pyroligneous liquor and lower yields in non-condensable gases are environmentally advantageous, contributing to lower emission of polluting gases. Nones et al. (2015) found charcoal yields of 34 and 36% for *E. benthamii*de, at 5 and 13 years of age, respectively, similar to those found in this study. On the other hand, Lima et al. (2007) studied the same species, but at 6 years of age, and observed a charcoal yield of 34.86%, slightly lower than the average

Table 4 Mean values for basic wood density, apparent relative density of charcoal and energy density

Species	DB	DEm	DRA	DEc
Eucalptus benthamii	493 b	2.28 b	415 a	3.16 a
Eucalptus dunnii	541 a	2.52 a	422 a	3.15 a
Eucalptus grandis	411 c	1.86 c	209 c	1.57 c
Eucalptus saligna	472 b	2.20 b	216 c	1.60 c
Eucalptus urograndis	465 b	2.13 b	299 b	2.24 b

DB = wood basic density (g cm^{-3}), DEm = energy density of wood (Gcal m^{-3}), DRA = apparent relative density of charcoal (g cm^{-3}), DEc = energy density of charcoal (Gcal m^{-3})

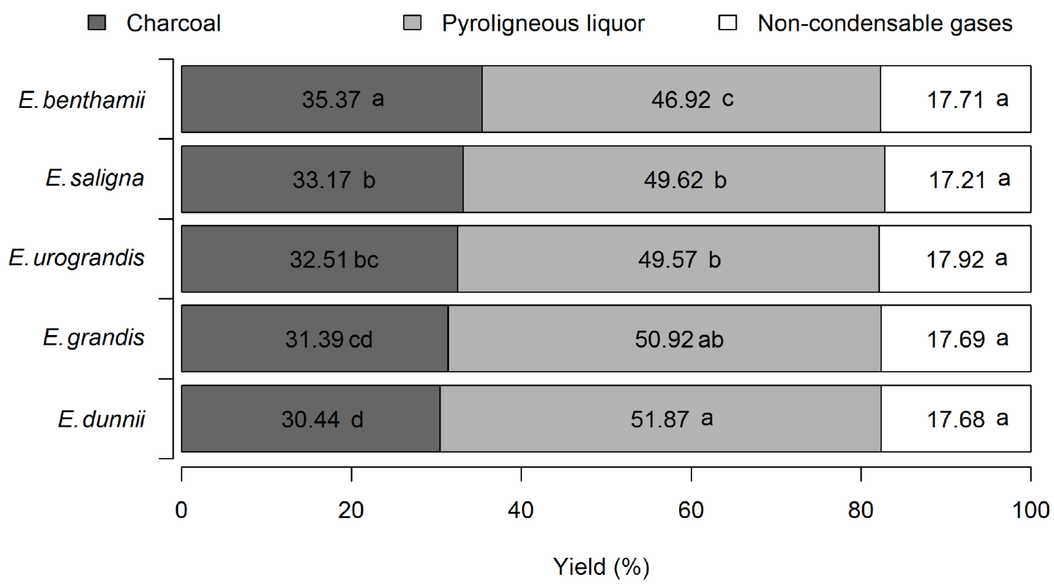

Figure 1 Average gravimetric yields in charcoal, pyroligneous liquor and non-condensable gases in *Eucalptus* spp.

value found in this study. It is worth noting that, in this study, the final carbonisation temperature was 500 °C. For the hybrid *E. urograndis*, Oliveira et al. (2012) found yields of 33.5% for charcoal, 38% for pyroligneous liquor and 28.5% for non-condensable gases. Since there was no significant difference in the mean high heating value and fixed carbon content of charcoal among species, charcoal yield was the predominant property in the differentiation between species for fixed carbon and energy yields. Thus, a significant effect of species was observed for both properties (Figure 2).

The species *E. benthamii* had the highest yields in energy and fixed carbon. Despite the highest basic wood density and apparent relative density of charcoal, *E. dunnii* had a negative performance, showing the lowest charcoal yields, fixed carbon and energy. The lower lignin content in the wood of this species resulted in lower coal yield. Lignin is the most thermally stable compound in wood (Basile et al. 2017). The average values for fixed carbon yield found in this study were similar to those found by Neves et al. (2011), Assis et al. (2012) and Protásio et al. (2013), with the exception of *E. dunnii* and *E. grandis*, which presented lower FCY. In general, materials with higher yields in fixed carbon and energy are in accordance with those required for charcoal production. The fixed carbon yield represents the amount of carbon present in wood and is retained in charcoal, thus, it is influenced by elemental components present in the biomass (ASSIS et al. 2012). Therefore, biomass with higher fixed carbon yields are those that mostly retain carbon, a property that is desirable in

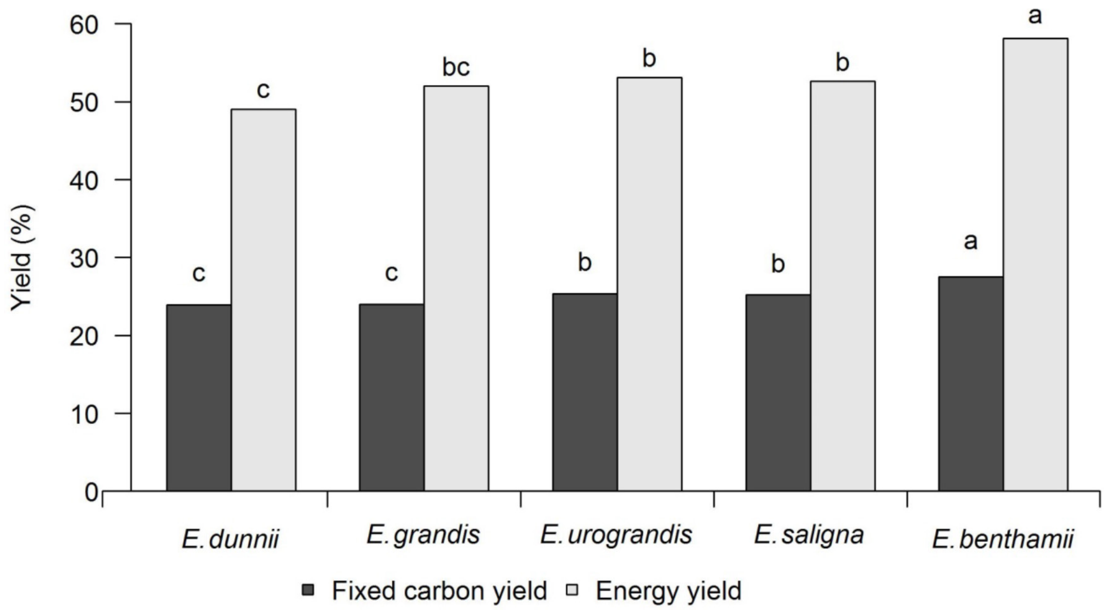

Figure 2 Fixed carbon and energy yield in *Eucalptus* spp.

bioreducers, just as the energy yield represents the amount of energy of the raw material (wood) that is stored in the final product (charcoal).

CONCLUSIONS

Based on the results, it can be concluded that, among the studied species, *E. benthammi* is the most suitable for charcoal production, with higher yield in charcoal, fixed carbon and energy. Regarding wood properties, density cannot be used as the only parameter for determining material selection. Fixed carbon content and charcoal yield should also be considered, although a denser wood produces a denser charcoal. For the carbonisation conditions used, with the exception of density, charcoal quality was not influenced by species.

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