

Energetic potential of *Eucalyptus* sp. wood cultivated in the Plaster's Pole of Araripe, PE, Brazil

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ABSTRACT: This study aimed to characterize the wood energetically and evaluate the quality of the charcoal produced from different *Eucalyptus* sp. clones, identifying the most suitable. The basic density of wood and was determined, then, the proximate chemical analysis and the calorific value were determined from charcoal. The annual energy production was estimated by the relationship between the wood production of these *Eucalyptus* clones and the information obtained in the previous steps. The experiment was conducted following a completely randomized design. The data were submitted to the homogeneity test of Cochran's variances when they presented significant differences, the means were compared by Tukey ($p = 5\%$). The properties of wood and charcoal were correlated by Pearson's correlation analysis ($p = 0.05$). According to the results, the genetic material didn't influence the chemical composition of charcoal, however, the clones of the *E. urophylla* × *E. tereticornis* hybrids - C101 and *E. urophylla* - C39 showed better results concerning the basic density of the wood. In addition, the C101 hybrid showed the greatest wood production, as well as the mass of charcoal to be produced. Due to these characteristics, this hybrid presented a greater potential for annual energy production.

Key words: biomass; brazilian semiarid; charcoal; energy matrix

Potencial energético de madeira de *Eucalyptus* sp. cultivado no Polo Gesseiro do Araripe, PE, Brasil

RESUMO: Este estudo teve como objetivo caracterizar energeticamente a madeira e avaliar a qualidade do carvão produzido de diferentes clones de *Eucalyptus* sp., identificando o mais adequado. A densidade básica da madeira foi determinada, em seguida, a análise da química imediata e o poder calorífico foram identificados do carvão vegetal. A produção anual de energia foi estimada pela relação entre a produção de madeira desses clones de *Eucalyptus* e as informações obtidas nas etapas anteriormente citadas. O experimento foi conduzido seguindo um delineamento inteiramente casualizado. Os dados foram submetidos ao teste de homogeneidade de variâncias de Cochran's, quando eles apresentavam diferença significativa, as médias foram comparadas pelo teste de Tukey ($p = 5\%$). As propriedades da madeira e do carvão vegetal foram correlacionadas pela análise de correlação de Pearson ($p = 0,05$). De acordo com os resultados, o material genético não influenciou a química imediata do carvão vegetal, entretanto, os clones de *E. urophylla* × *E. tereticornis* híbrido - C101 e *E. urophylla* - C39, apresentaram melhores resultados considerando a densidade básica da madeira. Além disso, o híbrido C101 apresentou o maior potencial de produção de massa de madeira, bem como a massa de carvão a ser produzida. Devido a essas características, esse híbrido apresentou maior potencial de produção anual de energia.

Palavras-chave: biomassa; semiárido brasileiro; carvão vegetal; matriz energética

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Introduction

Historically, forest biomass has had an important role in the energy matrix and has been widely used as a renewable source of energy. Thus, it has stirred interest to improve the quality of the carbonization system to increase the efficiency of the process when applied at its secondary source in the steel sector or even in domestic use (Trugilho et al., 2015). According to the National Energy Balance (EPE, 2019), biomass is a renewable resource in the Brazilian energy matrix, constituting about 8.5% of the energy generated, second only to hydraulic energy and natural gas, which are non-renewable resources and contribute 66.6 and 8.6%, respectively.

For energy demand, some Brazilian regions need forest biomass to complement the raw material required to generate energy. Such problem occurs in the Araripe region of, within the semiarid of Pernambuco, where the Plaster's Pole of Araripe is located. Regarding the exploitation of gypsum, a mineral that turns into plaster after dehydration, the region comprises 22 mines, with 153 gypsum calciners operating on forest biomass, and 420 plasterboard industries, consuming ~ 54.390 m³ of firewood per month (Gadelha et al., 2018).

In this context, it is necessary to expand the variety of raw materials used for energy production in this region, since a large part of the biomass used by these industries exploits the Caatinga; the dominant semiarid vegetation. One alternative is the implantation of plantations of fast-growing species that are specifically destined for energy use, since they are renewable sources, seeking affordable production costs for the calcining industries and rural producers in the semiarid region. However, it is necessary to better understand the characteristics of the biomass that will be used for this purpose.

The characteristics that directly influence the quality of wood and charcoal (a secondary product) are basic density, high percentages of charcoal yield, high fixed carbon content and a low percentage of volatile matter and mineral residues (Reis et al., 2012). These properties are related to calorific value and, consequently, energy efficiency. Other physical, chemical, mechanical, and anatomical properties must also be considered and are correlated to the energy characteristics of the raw material. This desirable set of properties is found in several exotic species of the genus *Eucalyptus* that are

widely used for energy purposes and well adapted to Brazilian edaphoclimatic conditions, allowing them to develop rapidly (Trugilho et al., 2015).

Therefore, it is necessary to understand the properties of wood and charcoal and their variations, as well as to relate them to the characteristics of the plantation from which the material originates. Thus, the aim of this work was to energetically characterize the wood and to evaluate the quality of the charcoal produced from different *Eucalyptus* sp. clones grown in the Pernambuco semiarid region, as well as identify which clone(s) are best for energy production according to their wood and charcoal properties and field characteristics.

Materials and Methods

Study area and sampling

Samples of six *Eucalyptus* sp. genetic materials were used (Table 1), from a plantation at the Experimental Station of the Instituto Agronômico Pernambuco (IPA) located in Chapada do Araripe, Araripina municipality (07°29'00" S; 40°36'00" W), semiarid region of Pernambuco state, in Brazil. The locality has red-yellow latosol soil and the climate is hot and dry with summer rains, classified as DdB' 4a' according to Köppen (Silva et al., 2016, 2017).

The plantation was installed in March 2002, with a spacing of 3.0 × 2.0 m, and the first harvest was carried out in 2009 when trees were 7.5 years old. The wood used in this study came from the second growth and was 5.5 years old, which was collected in June 2015. According to Gadelha et al. (2018), the second growth obtained the Average Annual Increment (AAI) values well below those of the first growth due to a severe drought that occurred in 2012 and 2013. However, such AAI values were still higher than those for Caatinga vegetation.

After cutting the trees, disks were removed at the positions of 0, 50 and 100% of the commercial height of the bole, considering a minimum diameter of 5.0 cm. Five trees were sampled for each treatment. The wood density was obtained for each disc, while for proximate analysis and the calorific value of wood and charcoal composite samples consisted of the homogenization of the chip discs.

Determination of basic wood density

The procedure used to analyze the basic wood density was the NBR 11941 standard (ABNT, 2003).

Table 1. Description of the *Eucalyptus* sp. genetic materials with their respective clone identifications and the average annual increment (AAI) from an experiment developed at the Experimental Station of the Instituto Agronômico de Pernambuco (IPA), in Araripina, PE, Brazil.

Treatment	Genetic materials	Code	AAI (m ³ ha ⁻¹ year ⁻¹)
T1	Hybrid of <i>E. urophylla</i> × <i>E. tereticornis</i> of Laura (controlled pollination)	C80	9.17
T2	Hybrid of <i>E. urophylla</i> × <i>E. tereticornis</i> of Laura (controlled pollination)	C101	12.65
T3	Hybrid of <i>E. urophylla</i> (natural crossing)	C39	13.65
T4	Hybrid of <i>E. urophylla</i> × <i>E. tereticornis</i> of Laura (controlled pollination)	C158	10.04
T5	Hybrid of <i>E. urophylla</i> (natural crossing)	C41	10.30
T6	Hybrid of <i>E. urophylla</i> (natural crossing)	C33	5.18

Carbonization

After determining the basic density, the discs were reduced to chips to obtain composite samples for each treatment. From this, five repetitions were obtained for carbonization and proximate analysis of the resulting charcoal.

The carbonization process took place in a Mufla type reactor, with adaptation, for 210 minutes. For this, 100 g of wood chips were used per repetition, in which the material remained at a temperature of 150 °C during the first 30 min, subsequently it was raised to 250 °C for another 30 min. After this period, a heating rate of 1.4 °C min⁻¹ was applied, which was maintained until reaching 460 ±10 °C, which ended with the carbonization process (Vale et al., 1996).

Proximate chemical analysis of charcoal

After the carbonization process, the gravimetric yield (%) in charcoal was determined by dividing the dry charcoal mass by the dry wood mass. The proximate chemical of charcoal was carried out by analyzing the D1762-84 standard (ASTM, 2013a) to determine the contents of volatile matter, ash, and fixed carbon on a dry basis. The yield of fixed carbon was obtained by the product of the gravimetric yield of carbonization and the fixed carbon content of charcoal.

Determination of calorific value

The high calorific value (HCV) of the wood was obtained in a calorimeter (IKA® WERKE C5003 model) following the D5865 standard (ASTM, 2013b). The calorimeter was calibrated based on heating of benzoic acid PA, resulting in 2,959 ± 30.4 cal °C⁻¹ (CV = 1.03 %). This value was used to determine the HCV, according to Equation 1. The analyzes were performed in duplicate. For charcoal production, the HCV was estimated from Equation 2, defined by Vale et al. (2002).

$$SCV = \frac{C \cdot \Delta T}{m} \quad (1)$$

where:

- HCV - high calorific value, cal g⁻¹;
- C - 2,959 ± 30.4 cal °C⁻¹;
- ΔT - temperature variation, °C; and,
- m - wood mass, g.

$$HCV_{\text{charcoal}} = 4,934.43 + 33.27 \cdot \%FC \quad (2)$$

where:

- HCV_{charcoal} - charcoal's high calorific value, cal g⁻¹; and,
- %FC - fixed carbon content in charcoal, %.

For each species, the lower calorific value (LCV) of wood and charcoal were estimated as proposed by Brand (2010), as shown in Equation 3. For this calculation, the average values of hydrogen used for *Eucalyptus* sp. were defined according to the literature, which are: 3.34 % for charcoal (Oliveira et al., 1982; Assis et al., 2012; Protásio et al., 2013; Soares et al., 2014), and 6.0 % for wood (Brand, 2010).

$$LCV = HCV - 600 \cdot (0.09 \cdot H) \quad (3)$$

where:

- LCV - lower calorific value, cal g⁻¹;
- HCV - high calorific value, cal g⁻¹; and,
- H - hydrogen, %.

Estimated annual energy production

This step was carried out to determine the potential energy production of charcoals from different *Eucalyptus* sp. genetic materials. For this, the dry mass of wood was obtained (kg ha⁻¹ year⁻¹) based on basic wood density (kg m⁻³) and the average annual increment (m³ ha⁻¹). The annual amount of charcoal (kg ha⁻¹) produced from this wood was estimated by relating the dry mass of wood to its gravimetric yield in charcoal. The carbon mass was estimated (kg ha⁻¹ year⁻¹) by relating the mass of charcoal and the fixed carbon content in charcoal. Finally, the amount of energy that would be produced annually (kcal year⁻¹) with this charcoal was obtained from the relationship between the charcoal mass and the high calorific value of the charcoal (kcal kg⁻¹).

Then, the amounts of electricity produced annually by each clone were estimated, based on the basic relationship in which 1 kcal = 0.00116 kwh (Santos et al, 2013). Finally, to calculate the theoretical potential of conversion to electrical energy, the average efficiency was 20% (Nogueira & Lora, 2003).

Statistical analysis

The design used was entirely random. The data obtained was subjected to the Cochran's homogeneity test and compared using analysis of variance (ANOVA). For samples that showed a statistical difference between the treatments according to the F test, the means were compared for the analyzed variables using the Tukey test at 5% probability. Finally, a Pearson correlation analysis was performed between the properties of wood and charcoal, with a significance level of p = 0.05. All analyzes were performed using RStudio software version 3.6.3.

Results

Basic density of wood

The average for basic wood densities ranged from 0.53 to 0.64 g cm⁻³ (Figure 1) and are classified as medium density wood. The treatments T1 and T2, which correspond to clones C101 and C41, respectively, presented the highest values for this variable.

Proximate chemical analysis of charcoal

According to the ANOVA, statistical differences were only observed between treatments for ash contents (Table 2), whose differentiation of the means for this variable is shown in Table 3. As the other variables did not show statistical difference, the correspondent letters referring to the Tukey

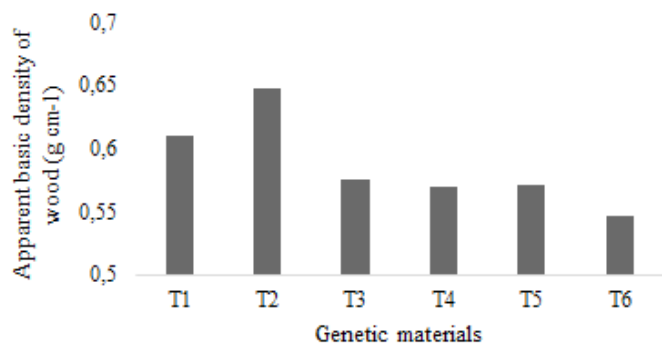


Figure 1. Average values of basic density of *Eucalyptus* sp. with 5.5 years from planting at the Experimental Station of the Instituto Agrônomico Pernambuco (IPA), in Araripina, PE, Brazil.

test for them were not added in the table. The data showed homogeneous variances.

Calorific value of wood and charcoal

The values obtained from the LCV can be found in Figure 2, varying between 4,109 and 4,303 kcal kg⁻¹ for wood, with the highest value corresponding to T1, and varying between 6,351 and 6,890 kcal kg⁻¹ for charcoal.

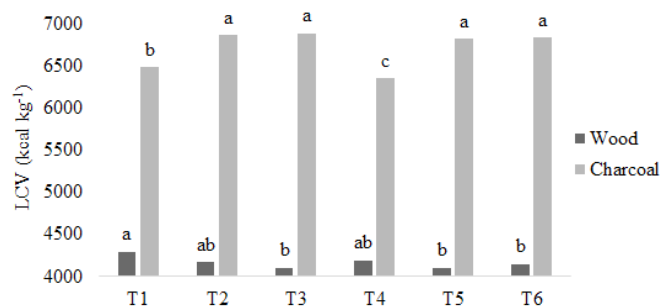


Figure 2. Lower calorific value (LCV) of wood (coefficient of variation = 0.89 %) and charcoal (coefficient of variation = 0.66 %) of *Eucalyptus* sp. clones with 5.5 years of planting at the Experimental Station of the Instituto Agrônomico Pernambuco (IPA), in Araripina, PE, Brazil.

Estimated annual energy production

According to the results presented in Table 4, clone T2 presents the highest estimate of annual energy production, and T6 presents the lowest production.

Correlation analysis

From the correlation analysis in Figure 3, only the ash content correlates to the basic density of *Eucalyptus* sp.

Table 2. Analysis of variance of the proximate analysis of charcoal from *Eucalyptus* sp. genetic materials originating from an experimental plantation in Araripina, PE, Brazil.

Variation source	GL	"F" values						Variation source	GL	"F" value
		%Ash	%VM	%GY	%FC	%FCY	LCV charcoal			
Treatments	5	66.62*	0.65 ^{ns}	1.75 ^{ns}	0.44 ^{ns}	0.93 ^{ns}	108.35*	Treatments	5	7.47*
Residue	18							Residue	6	
Total	23							Total	11	

Where: ns - not significant at 5 % probability; * - significant at 5 % probability; GL = degrees of freedom; VM = volatile matter; GY = gravimetric yield; FC = fixed carbon; FCY = fixed carbon yield; LCV = lower calorific value.

Table 3. Average results for the contents of Ash (%Ash), volatile matter (%VM), gravimetric yield (%GY), fixed carbon (%FC), and fixed carbon yield (%FCY) from charcoal treatments that originated from *Eucalyptus* sp. genetic materials from an experimental plantation in Araripina, PE, Brazil.

Treatments	%Ash	%VM	%FC	%GY	%FCY
T1	0.96 b	38.88	62.08	33.70	20.55
T2	1.32 a	38.50	62.2	33.19	21.10
T3	0.39 cd	37.93	62.46	33.02	22.49
T4	0.52 cd	38.26	62.26	32.83	20.51
T5	0.59 c	38.45	62.14	33.33	21.32
T6	0.35 d	38.12	62.22	32.62	20.46
Mean	0.69	38.36	62.33	33.11	21.07
CV (%)	13.58	2.14	1.31	1.75	7.7

Means followed by the same letter do not differ statistically from each other according to the Tukey test at a 5 % probability level.

Table 4. Estimated annual production of energy produced from charcoal originating from different *Eucalyptus* sp. genetic material from an experimental plantation in Araripina, PE, Brazil.

Treatments	Dry wood mass (kg ha ⁻¹ year ⁻¹)	Volume of wood (m ³ ha ⁻¹ year ⁻¹)	Charcoal mass (kg ha ⁻¹ year ⁻¹)	Carbon mass (kg ha ⁻¹ year ⁻¹)	Potential energy	
					(kcal ha ⁻¹ year ⁻¹)	(kwh ha ⁻¹ year ⁻¹)
T1	5,590	9.56	1,890	980	2,510	2,921.36
T2	8,180	12.78	2,720	1,720	3,840	4,457.54
T3	7,490	12.91	2,440	1,540	3,440	3,995.78
T4	5,720	10.79	1,880	900	2,450	2,852.50
T5	5,880	9.19	2,010	1,250	2,810	3,269.60
T6	2,830	5.15	920	580	1,360	1,505.68

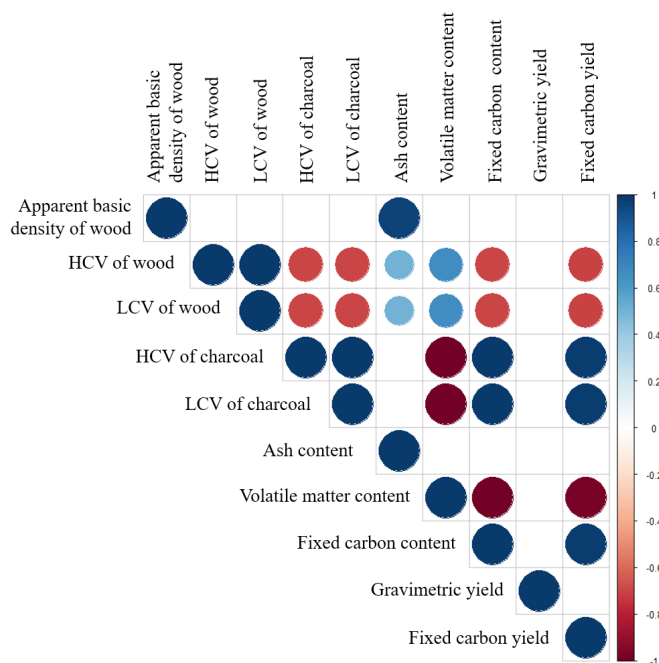


Figure 3. Correlation analysis between the variables: basic wood density; High calorific value (HCV) and lower calorific value (LCV) of wood; high calorific value (HCV) and lower calorific value (LCV) of charcoal; Ashes; volatile matter; fixed carbon; gravimetric yield and fixed carbon yield.

wood, with no interaction between the calorific value of the wood and others charcoal characteristics. Additionally, the ash content was not influenced by any other charcoal characteristics. The characteristics in white in Figure 3 no presented correlation.

Discussion

Basic density of wood

In general, the wood of the genus *Eucalyptus* used to produce charcoal has a basic density of $\sim 0.54 \text{ g cm}^{-3}$, which is considered a medium density (Silveira et al., 2013; Carneiro et al., 2014). Thus, the values obtained in this study corroborate using this wood for the charcoal production. However, the values are still below what is normally found in Caatinga species, which are denser than *Eucalyptus* species and, in turn, have longer combustion and greater potential for energy production (Protásio et al., 2013). On the other hand, they have higher average annual increments and shorter rotations, which directly contributes to mitigate the effects of deforestation of Caatinga vegetation by offering more wood in less time (Silva et al., 2016, 2017).

Studying this variable is particularly important for determining the quality of charcoal. According to Vale et al. (2010), the basic density is linked to the production of charcoal and its quality, being one of the properties that most influences in the final product.

The apparent basic density of wood is an important characteristic that directly influences the planning of wood energy use, especially when considering the dimensions of

biomass for transportation (Brand, 2010). Since the clones used herein were all classified as medium density, they would have a substantial mass/volume ratio, which could cause difficulties for transportation. Brand (2010) also states that the density influences the dimensions of the wood parts that are used in the furnaces, as well as the dimensions of the power generation unit, depending on the yield and energetic efficiency of the biomass.

Proximate chemical analysis of charcoal

Regarding the percentage of ash, most of the results fall within the expected range, since they varied from 0.35 to 1.32%. The values obtained were close to those found by Reis et al. (2012), who found between 0.44 % and 0.81 % in a study carried out with *E. urophylla* clones. However, the T2 treatment showed the highest percentage among the six clones (1.32%). This clone differed statistically from the others, as well as T1. The lowest values were observed in T3, T4, and T6. The variations in ash contents may have occurred due to the location influencing the mineral composition of each tree or the presence of impurities from the field during cutting, harvesting, transport, or storage phases.

Therefore, low quantities of these elements are desirable since these minerals do not participate in the combustion process. Besides, a high ash content may indicate contamination by soil residues, cause the furnace in which it is being burned to deteriorate, and, if used for steelmaking, impair the quality of pig iron (Santos et al, 2016).

The values referring to the fixed carbon yield varied between 20.46 and 22.49% and did not present significant differences between the clones' means. These values are lower than charcoal from *Eucalyptus* sp. found in the literature, i.e., close to 25% (Protásio et al., 2013).

The relationship between volatile compounds and carbon fixed in charcoal is inversely proportional. The values for volatile matter (35.42 to 37.97%) were higher than those found in the literature (Reis et al., 2012; Soares et al., 2014; Santos et al., 2016) consequently, the levels for fixed carbon (62.08 to 62.82%) were below expectations.

Regarding the contents of volatile matter and fixed carbon, the opposite is desired, that is, the content of volatile matter should be lower and that of fixed carbon should be higher. These characteristics would provide a slower burning charcoal, improving its quality (Brand, 2010; Reis et al., 2012).

The variable yield of fixed carbon covers characteristics of charcoal productivity and quality, so the higher the yield, the more favorable the properties for energy purposes (Soares et al., 2014). Therefore, if higher yields of fixed carbon were obtained, the quality of charcoal produced from the materials used herein would also be higher.

Regarding the gravimetric yield, there was a conversion of firewood to charcoal in a proportion of 3 to 1. Thus, the results were satisfactory, since the higher the gravimetric yield, the more wood will be transformed into coal in the process, thus having a better use of raw material.

Calorific value and estimated annual energy production

The results found for the high calorific value (HCV) of the wood varied between 4,426 and 4,594 kcal kg⁻¹ and are close to those found by Juizo et al. (2017) for clones of *Eucalyptus*, corresponding to values between 4,468.33 and 4,753.33 kcal kg⁻¹. Since this value considers the heat obtained by recovering hydrogen in combustion, the energy characteristics from the value of the lower calorific value (LCV) were observed as expressing the effective value available for burning in the combustible material.

These values may have been influenced by the carbonization methods adopted herein, considering the final temperature and exposure time at the end of the process. According to Silva et al. (2018), charcoal quality is determined by the final combustion temperature and the speed of heating to convert wood into charcoal. The lowest values for the LCV were obtained by clones T1 and T4, with the others showing no significant difference. For wood, the clones showed a certain homogeneity of this characteristic since their values varied only slightly.

According to Brand (2010), the average calorific value of woody materials *in natura* with 25% humidity is close to 3,300 kcal kg⁻¹, as well as the average HCV and LCV values of charcoal are 6,800 and 6,500 kcal kg⁻¹, respectively. Therefore, the LCVs found in this work are considered satisfactory to produce energy from this raw material, corroborating the use of these clones for this purpose.

It is observed that eucalyptus plantations in the semi-arid regions can present wood production above 10 m³ ha⁻¹ year⁻¹. And, from this production, they are able of generating about 2.5 tons of charcoal per year.

It is estimated that the annual consumption of firewood to supply plaster production at the Araripe Pole is 652,680 m³ (Gadelha et al., 2018). Regarding the best genetic material from the annual energy production of charcoal produced by these *Eucalyptus* sp. clones, the T2 clone had the best results, according to the annual production of wood. Therefore, extrapolating the values, considering only the volume of wood and not the amount of energy produced, it would take about 50,550 hectares of plantations for this clone to supply the annual energy demand of the industries located in that region.

Depending on the genetic material grown, there may be a greater fixation of carbon mass in this wood, and among the clones studied, clone T2 also stood out for its high volumetric production, being the second one with the highest production among the six clones. This way, in addition to presenting great energy potential, its planting can contribute to alleviate some environmental problems resulting from climate change, through the accumulation of carbon in the standing biomass.

Correlation analysis

The correlation between wood density and the other important properties for charcoal production is always mentioned in articles with this theme. However, the authors are not always able to support the existence of this correlation. Considering the charcoal yield variable along with the basic density, Vital et al. (1986) found negative results regarding

this correlation. On the other hand, Reis et al. (2012) found a positive correlation between charcoal yield and density in studies with *E. urophylla*. In this work, the density showed a positive correlation only with the ash content, which often showed values above those found in the literature. Therefore, this high content of inorganics can influence the weight of biomass as a function of volume.

The calorific value is a variable that is influenced by the percentage of fixed carbon and mineral residues, which can contribute or hinder its performance. The LCV is positively influenced by the percentage of fixed carbon since the higher this content, the more carbon there is available for burning and the longer the material will last. On the other hand, volatile matter and ash content are inversely proportional to the calorific value since the former are released during burning and the ash does not contribute to combustion, which is considered waste at the end of the process (Carneiro et al., 2014).

The calorific value of charcoal showed a significant negative correlation with the content of volatile matter, as well as a positive one with the content of fixed carbon and its yield in fixed carbon. As previously discussed, the amount of fixed carbon and volatile matter have an inversely proportional relationship and a higher amount of carbon in charcoal is an indication of a better burning quality for a material.

Conclusion

The clones of the hybrid *E. urophylla* × *E. tereticornis* of Laura (controlled pollination) - C101 and the hybrid *E. urophylla* (natural cross) - C39 showed better results concerning the basic wood density.

As for the proximate chemical of charcoal, the genetic material only influenced the content of inorganic elements. In this way, among the material evaluated herein, these two clones are most indicated for charcoal production in the semiarid of Pernambuco.

These results contribute to the choice of raw materials with aptitude for energy production, and which present productive potential in semiarid regions. Therefore, the values found in the present study indicate that using *Eucalyptus* sp. is feasible for energy purposes and can be used to supply the demands of regions with high consumption of firewood and charcoal, and as an alternative to avoid cutting native vegetation.

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Compliance with Ethical Standards

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