Environment, Development and Sustainability
https://doi.org/10.1007/s10668-019-00418-0

Pyrolysis of *Anadenanthera peregrina* wood grown in different spacings from a forest plantation in Brazil aiming at the energy production

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Received: 2 October 2018 / Accepted: 6 July 2019

Abstract

The objective of this research was to evaluate the *Anadenanthera peregrina* wood cultivated in five spacing and pyrolyzed in two different heating rates. Three trees were collected from each spacing (3×2, 3×3, 4×3, 4×4 and 5×5 m), and samples were taken for the determination of the physical and chemical properties of the wood, the pyrolysis under the two heating rates (1.67 and 0.83 °C min^{-1}) and the subsequent analysis of the charcoal produced. Planting spacing did not influence the properties of *A. peregrina* wood. The heating rate influenced the charcoal properties, interacting with the spacing for the ash content and apparent density, yields of pyroligneous liquid and non-condensable gases.

Keywords Biomass and bioenergy · Pyrolysis and by-products · Sustainable silvicultural management

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1 Introduction

Since decades, it has been demanded by a high amount of forest-based products for various uses, specifically, by eucalyptus wood, for the supply of the raw material together with the production of firewood and charcoal. This fact resulted in scarcity of plantations, silvicultural management and studies of alternative species with high energetic potential that, consequently, could produce products and by-products with satisfactory properties and yields.

Charcoal is the main thermo-reducer of the Brazilian steel industry and is responsible for the large-scale production of pig iron and metal alloys, contributing significantly to the national economy. The references indicate that the country in the year 2017 produced an average of 6 million tons of the input, having almost all of them (± 85%), was directed to the steel industry (Ibá 2017). In addition, charcoal is present in the daily lives of the population, being widely used in residences, bakeries and steakhouses for food cooking and barbecue (Trugilho et al. 2001; Dias Júnior et al. 2015a; Ibá 2017). In general, Brazilian forest species are poorly researched, restricting the marketing of their products worldwide (Teixeira et al. 2011). Because of the variability of the wood, questions remain about the spacing of the ideal plantation to serve the most diverse wood products, mainly when the objective is the production of charcoal (Harrington et al. 2019; Inoue et al. 2011; Leles et al. 2011). Wide spacing results in larger diameter trees, while, in denser spacing, they provide greater competition between trees, resulting in rapid longitudinal growth (Magalhães et al. 2005; Inoue et al. 2011).

The specie *Anadenanthera peregrina* (L.) Speng, popularly known as "yopo, jopo and cohoba," has a wide geographical distribution and constitutes a wood with good properties for the construction and manufacture of furniture. In addition, it has potential for the production of firewood and charcoal, as it has high values of density and lignin content (Mori et al. 2003; Lorenzi 2009). Within the genus *Anadenanthera*, the species *A. peregrina* is the one that stands out most in geographical distribution in Brazil, because it has a great adaptability in environments with different types of shallow, deep or compacted soils, dry, humid or poorly drained (Carvalho 2003). The knowledge available about *A. peregrina* for energy purposes only addresses the lignin content that this species normally presents (Mori et al. 2003). The use of *A. peregrina* wood is often restricted in some of Brazil, limiting the sustainable management of the species. One of the explanations is that it has a high degree of allopathic effect on other species, hindering their insertion in forest restoration processes. In rural properties, the integrated planting of *A. peregrina* trees with other forest species, agricultural or livestock, in agroforestry systems or mixed plantations, could be an alternative, diversifying the production in a given area (Ribaski 2009; Amazonas et al. 2018).

Diversifying the use of timber species, especially native species, contributes to the valuation of plantations for the production of energy. If well planned, the integrated use of *A. pregrina* trees with eucalyptus or other forest species can subsidize ecologically and financially those areas in need of restoration, and that in most cases, the producer lacks the financial resources to maintain the installed restorative system (Pires et al. 2006; Amazonas et al. 2018). The development of research for the insertion of new species in the energy sector can also contribute to the standards of timber production technology and expand the Brazilian energy matrix. In addition to the final pyrolysis temperature, another approach such as the heating rate should be defined for *A. peregrina* wood, for better product efficiency, optimization and reduction in pyrolysis costs. The relevance of this variable impacts mainly on the yields and characteristics of charcoal produced and on its final use.

Thus, the hypothesis tested in this study is that the management of the plant spacing of *A. peregrina* in individuals considered young, and low rates of heat-action heating alter the properties of wood and pyrolysis products. The objective of this research was to evaluate the wood traits of *A. peregrina* cultivated in five spacings and pyrolyzed in two different heating rates.

2 Materials and methods

2.1 Origin and material sampling

The 56-month-old *A. peregrina* trees came from an experimental planting of the project called "Forest Pilot," located in Alegre city (20º 45' 49" S; 41º 31' 59" W; 245 m a.s.l), Espírito Santo State, southeastern region of Brazil. The objective of the pilot project was to characterize the genetics, growth and sequestration of carbon in plantations of non-traditional forest species in the south of the State of Espírito Santo to diversify the forest matrix. Had the support of the Research Support and Innovation of the Espírito Santo Foundation (FAPES), Federal University Espírito Santo (UFES) and miner Vale S/A.

The region presents dry winter and rainy summer, with average annual precipitation of 1300 mm and average annual temperature of 25 °C (Incaper 2018). *Anadenanthera peregrina* trees were planted under three types of soils, grouped in blocks (Fig. 1), and in five different planting spacings (3×2; 3×3; 4×3; 4×4; e 5×5 m).

In the year of 2015, the diameter census was carried out at 1.30 m of the soil (diameter at breast height, DAP), from this classification, three trees with a mean diameter by spacing

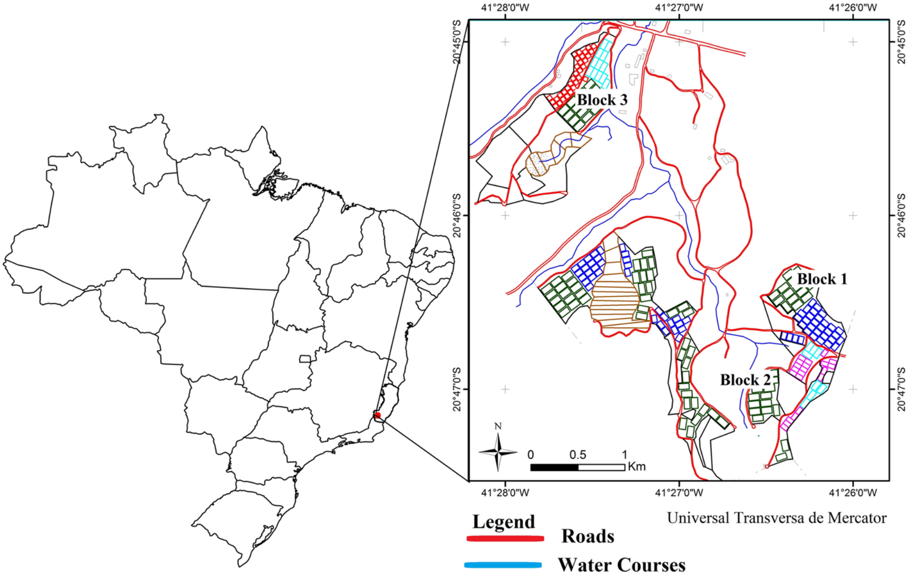


Fig. 1 Experimental area of the pilot project, where *A. peregrina* trees were planted in three types of soil (block 1, block 2 and block 3). *Source* From the author

Table 1 Dendrometric variables of the *A. peregrina* in function of the different spacings

Variables	3×2 m	3×3 m	4×3 m	4×4 m	5×5 m
Commercial height (m)	3.50	3.26	2.92	3.68	2.87
Total height (m)	7.94	7.68	7.84	8.36	8.06
Diameter at breast height (cm)	7.05	6.00	8.79	9.03	8.79

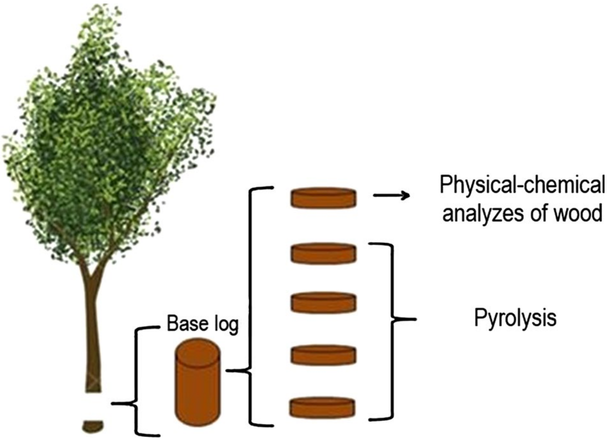


Fig. 2 Demonstration of material selection for the proposed analyzes. *Source* From the author

were randomly felled, totaling fifteen *A. peregrina* trees. The dendrometric characteristics are presented in Table 1.

From tree five, wood disks were extracted from the base three centimeters thick, totaling 75 disks (5 disks × 3 trees × 5 spacings). From the woody disks, opposite wedges were removed for determination of the basic density, chemical analysis and calorific value of the wood and the pyrolysis of the wood. A demonstration is presented in Fig. 2.

2.2 Wood assays

The basic density (BD) was determined according to the specifications of the Brazilian Regulatory Standard—NBR 11941(Abnt 2003).

The total extractives content was obtained by an extraction sequence in ethanol: toluene [1:2], ethanol and hot water, according to Technical Association of the Pulp and Paper Industry—TAPPI 264 (1996). The determination of the insoluble lignin content was made based on the descriptions of Gomide and Demuner (1986), the soluble lignin content was obtained according to the procedure described by Goldschmidt (1971), and the total lignin content was obtained by summing the insoluble and soluble lignin content.

To determine the ash content of the wood, the Brazilian Pulp and Paper Technical Association—ABTCP M 11/77 (Abtcp 1997), the gross calorific value (GCV) of the wood was obtained according to the methodology of NBR 8633 (Abnt 1984) and its determination was performed in adiabatic calorimeter Ika C200. The energy density (ED) was determined by the multiplication between the basic density (BD) of the wood and its respective gross calorific value (GCV), as presented in Eq. (1)

Table 2 Conditions of pyrolysis process of *A. peregrina* wood

Heating rate	Temperature (°C)		Heating rate (°C min^{-1})	Total time (h)
	Initial	Final		
T1	100	450	1.67	4
T2	100	450	0.83	7.5

$$\mathrm{ED} = \mathrm{BD} \times \mathrm{GCV} \tag{1}$$

where ED = energy density (MJ kg^{-1}); BD = bulk density (kg m^{-3}); and GCV = gross calorific value (MJ kg^{-1}).

2.3 Wood pyrolysis

The wood disks were previously dried outdoors for 30 days and then oven dried at 103 °C + 2 °C until reaching a constant mass (anhydrous condition). The samples wood was pyrolyzed under two heating rates in inert atmosphere with 30 mL/min nitrogen gas flow, according to Assis et al. (2012) and Arantes et al. (2013) as reported in Table 2.

The wood samples were placed in a metal crucible and inserted inside a muffle furnace, and a condenser coupled to a metal capsule into the electric furnace performed the condensation of the condensable gases (pyrolignous liquid). After pyrolysis, the gravimetric yields of charcoal (YC), pyroligneous liquid (YP) and non-condensible gases (YNCG) were determined. The determination of the apparent relative density of charcoal was obtained by immersing charcoal in water using the method described by Vital (1984) and determined by the relationship between its mass and volume. The immediate composition of the charcoal was carried out according to NBR 8112 (Abnt 1986), for the determination of volatile, ash and carbon contents.

The higher calorific value of the charcoal was determined using an adiabatic calorimeter, Ika C200 according to the recommendations of NBR 8633 (Abnt 1984). Thus, energy density was obtained by multiplying the apparent relative density of charcoal with its higher calorific value, similar to the procedure applied to wood (Eq. 1).

2.4 Data analysis

The data had the normality (Shapiro–Wilk) and homogeneity of the variances (Levene) tested. After testing these assumptions, the analysis of variance was performed by the F test at the 5% level of significance, and when this was significant there was the unfolding, we conducted the regression analysis to verify the trends as the variables are quantitative. Subsequently, the t test was applied to individually analyze the R^2 coefficients. Pearson correlations (t; $p < 0.05$) were performed between wood and charcoal parameters in an attempt to identify the relationships between the analyzed variables.

The main component multivariate analysis (ACP) was performed to explain the variance structure of the random vector composed by the characteristics evaluated in the wood, as described by Mingoti (2005) and Manley (2008). Only the averages of all the variables quantified in the wood were used, and the analysis of the main components was performed considering the standardized data (with unit variance). This procedure allows more accuracy in the analysis (Mingoti 2005). The relationship between variables (multicollinearity) is not a problem in this analysis. The basic objective of ACP is to obtain latent variables that represent linear combinations of a group of variables under study that are correlated (Ferreira 2008). Based on the dispersion of the scores of the main components considered, it was possible to evaluate the similarity or dissimilarity of the *A. peregrina* planting spacings and to group them into defined subgroups. The most similar ones belong to the same group, and the spacings that are heterogeneous with each other belong to different groups (Ferreira 2008; Lobão et al. 2010; Mingoti 2005). For the analysis of the main components, the correlation matrix of the data was used. The established linear combinations were interpreted by normalized eigenvectors and the correlations between the original variables and the main components. The analyses were conducted at 95% probability using the R Core Team software.

3 Results and discussion

3.1 Wood analysis

Table 3 summarizes the results of the properties of *A. peregrina* wood, without significant effect of the plant spacing on the basic density of the wood.

This was also observed for the species *Ateleia glazioviana*, *Acacia mearnsii*, *Eucalyptus grandis* and *Minosa scabrella*, in the first and third plant years (Eloy et al. 2014). However, if it were to compare the density results to the wood that has commonly been used for energy eucalyptus clones up to 6 years of age, the values of *A. peregrina* are relatively higher, from 0.374 to 0.64 g cm^{-3} (Castro et al. 2013; Dias Júnior et al. 2015a; Jesus et al. 2017; Magalhães et al. 2017). However, the results are within the range considered satisfactory (0.4–1.2 g cm^{-3}) for the production of charcoal (Brito et al. 1983; Trugilho et al. 2001; Carneiro et al. 2014). When the wood is subjected to pyrolysis, about 60% of its mass is lost, the higher the density, the greater the weight of the charcoal produced in a given volume and the higher the mechanical strength (Neves et al. 2011; Santos et al. 2011; Protásio et al. 2014). Plant spacing can influence, even if small, the density of hardwoods or not, depending on the species, clone or growth rate. Generally, plant spacing influences wood density by competition for sunlight, water, nutrients and other biotic factors necessary for tree growth. The high competition provided by denser plant spacings decreases the density of hardwood species (Benson 1963). Although these observations were not

Table 3 Properties analyzed in *A. peregrina* wood

Spacing	Area (m^2)	BD (g cm^{-3})	ET (%)	LIG (%)	AS (%)	GCV (MJ kg^{-1})	ED (MJ m^{-3})
3×2 m	6	0.64 ± 0.02	7.84 ± 0.98	24.80 ± 1.33	1.03 ± 0.02	19.08 ± 0.93	12,272 ± 124
3×3 m	9	0.69 ± 0.01	6.87 ± 1.11	24.51 ± 2.14	1.06 ± 0.31	18.69 ± 0.83	13,043 ± 198
4×3 m	12	0.68 ± 0.03	10.40 ± 1.01	23.50 ± 2.31	1.12 ± 0.22	19.31 ± 0.46	13,147 ± 301
4×4 m	16	0.64 ± 0.02	9.19 ± 1.61	24.93 ± 2.01	0.96 ± 0.24	19.67 ± 1.01	12,429 ± 325
5×5 m	25	0.65 ± 0.01	10.36 ± 0.97	24.83 ± 1.99	1.13 ± 0.24	19.27 ± 0.78	12,544 ± 327
Média	–	0.66	8.93	24.51	1.06	19.20	12,687

BD basic density; *ET* content extractives totals; *LIG* total lignin content; *AS* ash content; *GCV* gross calorific value; *ED* energy density observed in this study, it is possible that the species *A. peregrina* has a different physiological mechanism, is required older ages for better conclusions about the density ratio of the wood and spacing of planting.

Absolutely, the useful area of planting, however, the spacing only explained influenced about 30% the extractive content, being not significant by the regression analysis of the variables involved. There are some reports in the literature that the densification of trees, caused by smaller plant spacings, reduces the content of extractives in the wood (Browning 1963; Moulin et al. 2015). Nevertheless, the extractive content of the *A. peregrina* was superior to the one found for wood destined to the production of charcoal of different species of the cerrado biome, which varied from 5.26 to 7.76% (Costa et al. 2014; Vale et al. 2010). Eucalyptus wood ranges from 1.89 to 4.97% (Oliveira et al. 2010; Neves et al. 2011; Castro et al. 2013). The extractive content in the wood can contribute to the increase in the calorific value (when there are phenols in its composition) and of the carbon content, increasing the yield in fixed carbon of the fuel (Santos et al. 2011, 2016). Added to this, some classes of extractives are resistant to the action of heat on wood. This may contribute to the yields and characteristics of pyrolysis products, mainly by increasing the gross calorific value of charcoal.

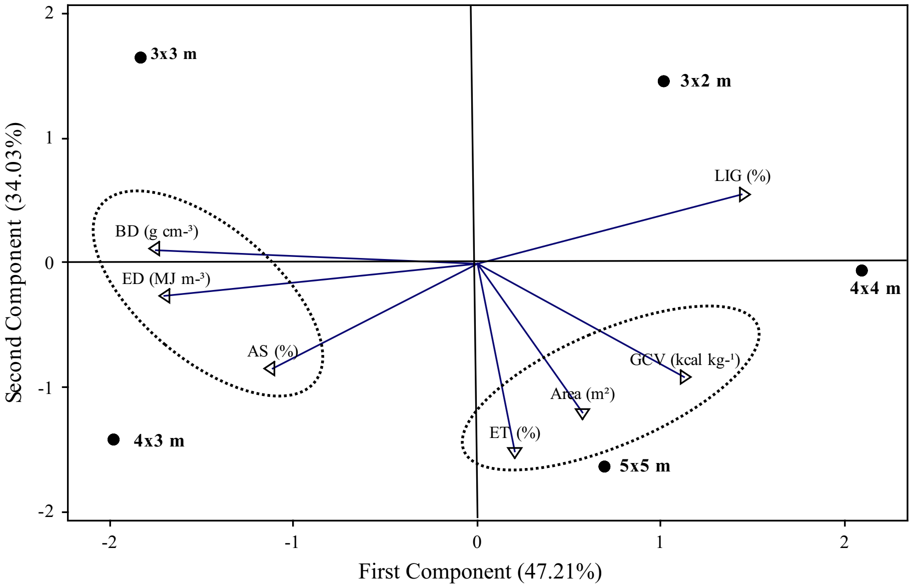
Similarly, the lignin content, the calorific power and energy density had no significant evidence spacing (Table 3). The lignin content had lower results than those observed for eucalyptus clones for energy generation, ranging from 27 to 33% (Oliveira et al. 2010; Neves et al. 2011; Castro et al. 2013; Carneiro et al. 2017). However, it is important to consider that the woody materials were from young individuals (56 months old), in a phase of "physiological maturation." Lignin and extractives are responsible for raising the calorific value of wood. The energy density depends on the calorific value and density of the wood. Thus, if lignin did not increase, the calorific value remains stable. Generally, the increase in density is a result of lignin content in woody species. As there was no significant increase in wood density, there was also no increase in lignin. Lignin is the chemical compound of wood that is more resistant to the action of heat. It is mainly responsible for the conversion of wood into charcoal. To obtain higher yields in charcoal and calorific value, the species must have high lignin content. This is one of the main variables to be considered in the selection of raw materials for the production of charcoal and energy.

For ash content, there was no significant effect between planting spacings (Table 3). The average ash content obtained was lower than that of the cerrado wood of the northeastern Brazil for energy production (1.80%) (Costa et al. 2014), higher than those of *A. peregrina* (0.35%), *A. colubrina* (0.50%) (Gonçalves et al. 2012) and those of energy eucalyptus, which have ash content, normally less than 1% (Brand et al. 2011; Neves et al. 2011; Pereira et al. 2013; Protásio et al. 2014). High ash content can damage the industrial process by forming crusts in equipment and pipes, causing the need to increase the frequency and expenses with the maintenance and cleaning of equipment (Barcellos et al. 2005; Brand 2010). Tropical woods have a variation in ash content, being this higher value in hardwoods and in younger trees. In eucalyptus wood, a trend of ash reduction was observed with advancing age (Santana et al., 2012; Protásio et al. 2014). This may be related to the decrease in the physiological activity of the tree and that favors the production of charcoal.

The variation between the values of the gross calorific value (GCV) of *A. peregrina* wood (Table 3) was similar to that found in the literature (Brand 2010; Brand and Muniz 2010). This is because, GCV is more related to the inherent characteristics of the species, for example, as the content and type of extractive present in the wood, which can contribute to the amount of heat released during the combustion of the material and influence the energy capacity of the fuel (Pereira et al. 2013; Carneiro et al. 2017). The lignin content also contributes to the elevation of calorific value, but it has been shown previously that this variable had no significant response in relation to the plant spacings studied. The average GCV value of the *A. peregrina* wood was close to the one obtained for the wood of another 100 Brazilian forest species, that is, 4732 kcal kg^{-1} (Quirino et al. 2014), and the values observed for different eucalyptus clones destined for energy, ranging from 4538 to 4867 kcal kg^{-1} (Brand and Muniz 2010; Brand et al. 2011; Santos et al. 2016; Jesus et al. 2017). The energy density (ED) of *A. peregrina* wood (Table 3) had values higher than those observed for eucalyptus wood clones planted for energy purposes, from 4125 to 12,196 MJ m^{-3} (Lemos et al. 2015; Magalhães et al. 2017).

From Fig. 3, it is observed that the three main components explain more than 80% of the variance of the evaluated data. The two components were considered in this study due to the large percentage of total variance explained by them. (The most relevant data sampled are contained in these main components.)

Analyzing the graphical distribution of the evaluated plant spacing, the separation of the physical and chemical variables, it is not possible to distinguish similar clusters of characteristics. In general, it is possible to notice the significant effect of the age of the red *A. peregrina* wood, being incipient at the moment of evaluation (56 months) on the properties of the wood. However, there is higher extractives content of higher calorific values for individuals grown in greater spacing (5 × 5 m) and proximity to individuals grown at 4 × 4 m spacing. *t* is observed that the high ash and lignin contents are placed oppositely, and the planted woods at the 4 × 3 and 3 × 2 m spacing, respectively.



Where: BD = basic density; ET = content extractives totals; LIG = total lignin content; AS = ash content; GCV = gross calorific value; ED = energy density.

Fig. 3 Diagram of ordering the scores and eigenvectors of the variables analyzed in the wood for the first and second main components. *BD* basic density; *ET* content extractives totals; *LIG* total lignin content; *AS* ash content; *GCV* gross calorific value; *ED* energy density

Table 4 Variables of pyrolysis and charcoal in function of the heating rate

Heating rate (°C min^{-1})	Variables				
	YC (%)	VM (%)	FC (%)	AC (%)	GCV (MJ kg^{-1})
1.67	36.56 ± 1.87	25.45 ± 0.56	72.72 ± 2.33	1.83 ± 0.11	29.50 ± 1.03
0.83	36.87 ± 1.98	24.53 ± 0.77	73.35 ± 1.97	2.12 ± 0.33	30.04 ± 0.78

YC yield charcoal; *VM* volatile material content; *FC* fixed carbon content; *AC* ash content; *GCV* gross calorific value; ± average standard error

Table 5 Variables of pyrolysis and charcoal in relation to plant spacing

Spacing	Planting area (m^2)	YC (%)	VM (%)	FC (%)	AC (%)	GCV (MJ kg^{-1})
3 × 2 m	6	37.46	24.36	73.68	1.96	29.95
3 × 3 m	9	36.69	25.43	73.07	1.50	30.04
4 × 3 m	12	36.09	24.50	73.21	2.29	29.62
4 × 4 m	16	36.91	25.06	73.19	2.31	29.37
5 × 5 m	25	36.45	25.59	72.04	2.37	29.87

YC yield charcoal; *VM* volatile material content; *FC* fixed carbon content; *AC* ash content; *GCV* gross calorific value; ± average standard error

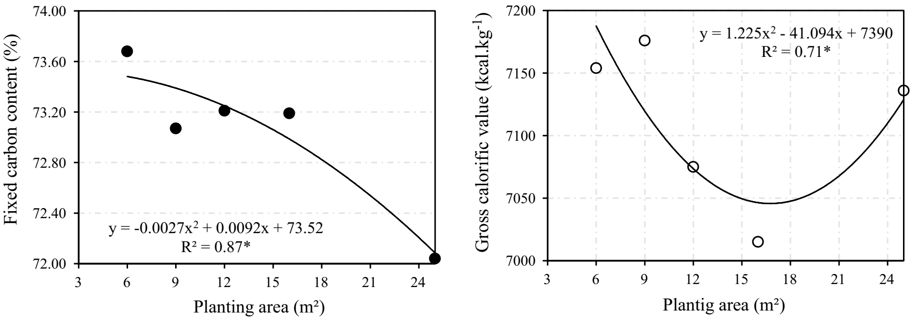


Fig. 4 Significant relationships between planting area (spacing) and charcoal variables of *A. peregrina* wood. *Significant at 95% probability ($p \leq 0.05$)

3.2 Pyrolysis and charcoal properties

There was no interaction between the heating rate and planting spacing on the variables related to pyrolysis of *A. peregrina* wood. However, when analyzing the factors individually (Tables 4 and 5), it is possible to observe absolute numerical differences.

Only fixed carbon content and calorific value had a significant effect on planting spacing (Fig. 4).

The charcoal yield was not influenced by the planting spacing nor by the heating rates, where the values remained around 35%. Similarly, they remained stable even when the wood was of different spacings; however, an increase is observed as a function of the increase in the heating rate (1.87 °C min^{-1}). It was previously shown that planting spacing did not influence the basic density and lignin content of *A. peregrina* wood. These are the two main variables that would result in the increase or diminution of the gravimetric yield in charcoal. However, the two rates of heating studied can be considered as the low impact to significantly change the yield and charcoal characteristics obtained from *A. peregrina* wood. The difference between the two heating rates studied is only 0.84 °C min^{-1}. It may be that the species presents a complex class of extractives, being allopathic, highly resistant to the action of heat, and rates of stronger heating (> 10 °C min^{-1}) should be studied later. When the heating rate increases, the charge flow in the pyrolysis also increases, which makes the heat action in the wood less effective and, consequently, results in higher contents of volatile materials. However, the values are in an acceptable range of 18.51–27.30% (Assis et al. 2012; Arantes et al. 2013; Rocha et al. 2017), in charcoal for the steel demand, for example.

Observing the confidence interval based on the standard errors of the fixed carbon averages, we note the effect of spacing and heating rates (Fig. 4). Although few differences exist between the densities of the wood from the spacing, the heating rate possibly acted specifically on each wood material. Thus, the values ranged from 72.04 to 73.68%. These values are considered regular for the use of charcoal against several uses reported in the literature (Assis et al. 2012; Pereira et al. 2012; Costa et al. 2014; Jesus et al. 2017; Rocha et al. 2017). For this variable, the higher the content is better. However, as it is obtained as a function of the final pyrolysis temperature, the charcoal yield must be analyzed before its final destination.

It is observed that the planting spacing and the heating rate were affected by the ash content of the coals produced (Tables 4 and 5). The highest values are observed in the charcoals produced by the heating rate 0.67 °C min^{-1} and for the planting spacing 5 × 5 m. According to Trugilho et al. (2005), the ash content varies according to several aspects, among them silvicultural management. In addition, when the lowest heating rate was applied, the wood was exposed for a longer time to the action of heat, contributing to an effective permanence of its minerals in the original product (wood) and the product obtained after pyrolysis (charcoal). This is related to the results observed in coals produced with eucalyptus and *Hymenaea courbaril* wood (Oliveira et al. 2010; Couto et al. 2015). It is important to note that high ash values can affect the burning of charcoal because it reduces fuel efficiency during combustion, for not generating heat.

The highest values obtained for the calorific value of the charcoal were for those produced with the lowest heating rate (0.67 °C min^{-1}). Despite being a variable little dependent on the properties of wood, its value oscillates as a function of the associated pyrolysis variables. This contributes to the results observed in coal produced with five-year-old eucalyptus wood, whose highest values were verified in the lower heating rates (Oliveira et al. 2010).

Differently from the discussed variables that presented very low correlations, which will be discussed below, had a small influence on the spacing and pyrolysis heating rates. It should be noted that *A. peregrina* wood is considered young, in a physiological process of formation. Thus, in Table 6, the small interaction between the heating rate and the plant spacing interferes with gravimetric yield and non-condensable gases.

There was a significant effect between heating rates on non-condensable gas (NCY) yields and pyroligneous liquid yield (YPL), but the same was not observed regarding planting spacings. The yield in non-condensable gases rose with the increase in the heating rate, while the yield in pyrolignous liquid decreased; however, the values obtained are within

Table 6 Variables of pyrolysis in relation to plant spacing and heating rate

Spacing	NCY (%)		YPL (%)		BD (g cm^{-3})		ED (MJ kg^{-1})	
	1.67 °C* min^{-1}	0.83 °C* min^{-1}	1.67 °C min^{-1}	0.83 °C min^{-1}	1.67 °C min^{-1}	0.83 °C min^{-1}	1.67 °C min^{-1}	0.83 °C min^{-1}
3×2 m	20.94	27.36	41.88	34.37	0.43	0.46	12,896	13,906
3×3 m	20.95	22.97	42.88	37.80	0.43	0.52	12,868	15,738
4×3 m	22.10	26.67	40.98	34.70	0.41	0.42	12,159	12,633
4×4 m	21.18	23.44	42.51	38.99	0.45	0.58	13,145	17,738
5×5 m	22.25	22.22	40.74	38.53	0.43	0.60	12,824	18,266

NCY non-condensable gas yield; *RLP* yield pyrolignous liquid; *BD* bulk density; *DA* energy density; *Heating rate

Table 7 Correlations between the properties of wood and charcoal of *A. peregrina*

Variables	Wood				
	Basic density	Total extractive	Lignin content	Ash content	High calorific value
Charcoal					
Bulk density	−0.212	0.081	0.566*	−0.172	0.271
Volatile materials	0.140	0.032	0.317	0.093	0.168
Ash content	0.117	0.665*	−0.235	0.297	0.209
Fixed carbon	0.182	−0.341	−0.179	−0.224	−0.251
Gross calorific value	0.175	0.075	0.109	0.054	−0.350
Charcoal yield	0.285	0.080	0.066	0.070	0.141

*Significant at 95% probability ($p \leq 0.05$)

what is usually observed in the literature: from 38.75 to 45.41% for YPL and from 19.70 to 21.92% for NCY (Dias Júnior et al. 2015a; Jesus et al. 2017; Rocha et al. 2017).

The higher values of apparent density were observed in the charcoals produced under the heating rate 0.83 °C min^{-1} and the wood resulting from the larger spacing. The lower heating rate, for the same final temperature, produces coals with higher densities in charcoals produced from wood of various forest species (Anta Junior et al. 2000). Under lower heating rates, there is greater efficiency of heat transfer and mass of the wood, as well as greater planting spacing allows for the greater development of the individuals; thus, these results are technically acceptable. The action of the heat provided by the pyrolysis degrades much of the main constituents of the wood, reducing its mass weight (Syred et al. 2006). High values of density result in the improvement in the mechanical resistance of charcoal and influence important operational, economic and productive aspects (Botrel et al. 2007; Protásio et al. 2015). When considering a specific use, for example, the density of the charcoal produced by *A. peregrina*, mainly those produced under the lowest heating rate (0.83 °C min^{-1}), is satisfactory for the domestic use for barbecue, and sometimes superior to those found for charcoals produced with eucalyptus wood (Neves et al. 2011; Assis et al. 2012; Dias Júnior et al. 2015b).

The energy density had the highest values associated with the heating rate 0.83 °C min^{-1} and the spacing 3×3, 4×4 and 5×5 m (Table 6). The higher the values for this variable, the more efficient it becomes the energy of the fuel potential. Thus, all the values obtained for the charcoal produced with *A. peregrina* wood can be considered satisfactory for the various energetic uses to be proposed (Magalhães et al. 2017).

Table 6 shows the correlations between the variables of wood and charcoal of *A. peregrina*.

There are correlations between the apparent density of the charcoal and the lignin content of the wood and between the ash content of the charcoal and the extractive content of the wood (Table 7). Generally, the ash content of the charcoal is related to the ash content of the wood and, to a lesser extent, to the total extractive content (Brito and Barrichelo 1977; Vital et al. 1986; Soares et al. 2014). Similarly, the relative density of charcoal is more related to the basic density when compared to the total lignin content of the wood (Vale et al. 2001, 2010; Brand et al. 2013; Costa et al. 2014; Protásio et al. 2015).

The increase in the lignin in the wood provides the increment of the apparent density of the charcoal, due to its higher resistance to pyrolysis. This is related to the chemical structure and the types of bonds existing in the lignin molecule, which reflects in a high resistance to the thermal degradation of the wood (Trugilho et al. 2001).

4 Conclusions

Planting spacing does not influence the physical and chemical properties of *A. peregrina* wood grown in Brazil.

The heating rate of the pyrolysis process interferes with the properties of the charcoal.

In some planting spacings, the heating rate influenced the ash content, bulk density, pyroligneous liquid yield and non-condensable gases yield.

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