EFFECT OF THE FINAL CARBONIZATION TEMPERATURE ON THE QUALITY OF FIVE SPECIES OF CERRADO

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Resumo

Efeito da temperatura final de carbonização na qualidade do carvão vegetal de cinco espécies do Cerrado. O objetivo da pesquisa foi caracterizar as propriedades energéticas do carvão de espécies provenientes do cerrado *sensu stricto*, assim como avaliar o efeito da temperatura final de carbonização. Foram selecionadas cinco espécies para estudo e das toras de cada espécie foram obtidos dez corpos de prova sendo dois tratamentos com cinco repetições cada. A densidade básica da madeira foi calculada pelo método da balança hidrostática. O carvão vegetal foi produzido por meio do processo de pirólise da madeira em um forno tipo mufla adaptado para captação do licor pirolenhoso, em que foram utilizadas duas marchas com temperaturas finais de 500 °C e 550 °C. Por meio do processo de pirólise foram obtidos os valores de rendimento gravimétrico total do carvão, rendimento em gás condensável e em gás não condensável. Determinou-se a densidade aparente, a análise química imediata (AQI) do carvão vegetal, e por fim calculou-se o seu poder calorífico. O RTC apresentou valores aceitáveis para as espécies *Terminalia glabrescens* (35,43 %) e *Vatairea macrocarpa* (32,59 %). O teor de materiais voláteis da espécie *Vatairea macrocarpa* (22,53%) apresentaram-se com valores satisfatórios. Os teores carbono fixo, de cinzas e do poder calorífico também foram considerados aceitáveis para *Terminalia glabrescens* (74,43%, 0,96% 7457,40 kcal.kg^{-1}), *Vatairea macrocarpa* (75,21%, 0,55% e 7443,57 kcal.kg^{-1}) e *Xylopia aromatica* (74,27%, 0,67% e 7365,56 kcal.kg^{-1}), apresentando alto potencial energético. O RTC, RGC e o RGNC sofreram influência das marchas de carbonização, assim como o teor de materiais voláteis. A temperatura final de carbonização recomendada foi a de 550 °C.
Palavras-chaves: Pirólise. Qualidade do carvão. Rendimento Gravimétrico.

Abstract

The objective of the research was to characterize the energetic properties of the charcoal from species from the cerrado *sensu stricto*, as well as to evaluate the effect of the final carbonization temperature. Five species were selected for study. Ten specimens were obtained from the logs of each species, submitted to two treatments with five replicates each. The basic density of the wood was calculated by the hydrostatic balance method. The charcoal was produced by the pyrolysis process of the wood in a muffle furnace adapted to capture the pyrolignous liquor, in which two heating speeds were used with final temperatures of 500 °C and 550 °C. Through the pyrolysis process, the total gravimetric yield of the coal, yield in condensable gas, and non-condensable gas were obtained. The apparent density, the immediate chemical analysis (ICA) of the charcoal was determined and, finally, its calorific value was calculated. The YC presented acceptable values for the species *Terminalia glabrescens* (35.43%) and *Vatairea macrocarpa* (32.59%). The volatile material content of *Vatairea macrocarpa* (22.53%) presented satisfactory values. Fixed carbon, ash and heat content were also considered acceptable for the species *Terminalia glabrescens* (74.43%, 0.96% 7457.40 kcal.kg^{-1}), *Vatairea macrocarpa* (75.21% 0.55% and 7443.57 kcal.kg^{-1}) and *Xylopia aromatica* (74.27%, 0.67% and 7365.56 kcal.kg^{-1}), presenting high energy potential. The YC, YL and YNNC were influenced by the heating speeds as well as the content of volatile materials. The recommended final carbonization temperature is 550 °C.
Keywords: Pyrolysis. Charcoal quality. Yield.

INTRODUCTION

Brazil stands out in the world as the largest producer and consumer of charcoal, being responsible for 11% of all charcoal produced globally, in which this input has a large scale industrial application, as the main destination is the production of iron pig iron, steel, ferroalloy and metallic silicon (IBÁ, 2019). The great demand for charcoal to supply the needs of the industry is one of the factors that contribute to deforestation, due to not having enough planted forests to supply all the demand, resulting in the disordered exploitation of native forests (COSTA *et al*., 2014).

According to the Minister of the Environment, half of the charcoal used in the steel industry is from native forest, often from the Cerrado (AGÊNCIA BRASIL, 2019). The Cerrado is a tropical savannah region in South America, including much of Central Brazil, part of the Northeast of Paraguay and East of Bolivia, being the second

Brazilian domain in extension. The Cerrado occupies approximately 22% of the Brazilian territory, in an estimated total area of 2,036,448 km² (MMA, 2015).

Tocantins is one of the Brazilian states with the largest area covered by the Cerrado biome (182,640 km²). About 72% of coverage with native vegetation is preserved, constituting one of the largest remnants of this biome (MMA, 2015).

Savanna formations, where the areas of cerrado *sensu stricto* are inserted, however, usually occupy flat land with deep soils ideal for mechanized agriculture, which permits the conversion of natural areas into crops and pastures. As a result, these formations have lost 64 million hectares, representing 47.84% of their original vegetation cover. This scenario is the highest annual deforestation rate among all Brazilian biomes, led by the states of Maranhão, Bahia and Tocantins (FERREIRA *et al*., 2017).

The wood from the Cerrado's land use substitution is reused. Through environmental licensing, the areas are deforested for implantation of pasture, generating a large amount of waste and one of the ways of disposing of this waste in the state of Tocantins is the production of coal. The Document of Forest Origin (DOF), instituted by the Ministry of the Environment (MMA) Ordinance No. 253, of August 18, 2006, is the license that allows native coal to be produced, stored and transported legally (IBAMA, 2018).

According to Costa *et al*. (2014), there is a need to encourage scientific research with native species from the Cerrado and the evaluation of the quality of wood and coal to ascertain the potential of the material to be used as an energy input, as this product is influenced by the wood that produced it and the production system. Thus, it is essential to determine the physical and chemical properties that relate to energy performance, such as basic density, volatile material content, fixed carbon, ash, and higher calorific value (SANTOS *et al*., 2016). The physical, chemical, anatomical, and mechanical properties of charcoal are affected, basically, by the intrinsic characteristics of the raw material that originated it, by the carbonization parameters and, also, by the production systems (BAILIS *et al.*, 2013).

The final carbonization temperature influences the yield of the solid, liquid and gaseous fractions of this process, in addition to having effects on the physical, chemical and energetic properties of charcoal, as well as on the apparent density, the content of volatile materials, ash, and fixed carbon and higher calorific value (ARAÚJO *et al*., 2018). Consequently, it is an important parameter to define the quality of this solid fuel (AZEVEDO *et al*., 2013; VIEIRA *et al*., 2013).

Due to the importance of charcoal and the need to study the energy potential of species in the Cerrado, this study aimed to characterize the energy properties of coal from species from the cerrado *sensu stricto*, as well as to evaluate the effect of the final carbonization temperature.

MATERIAL AND METHODS

Location and characteristics of the wood collection region

The samples of native wood from the cerrado *sensu stricto* used in this work were collected from trees felled in a land use substitution area in the municipality of Dueré, state of Tocantins, located on the geographical coordinates 11 ° 11'01.7 " South, 49 ° 22'05.6 " West.

The collection area has an environmental license and a Document of Forestry Origin (DOF), as the forest that is being replaced by pasture is reused for the production of native charcoal.

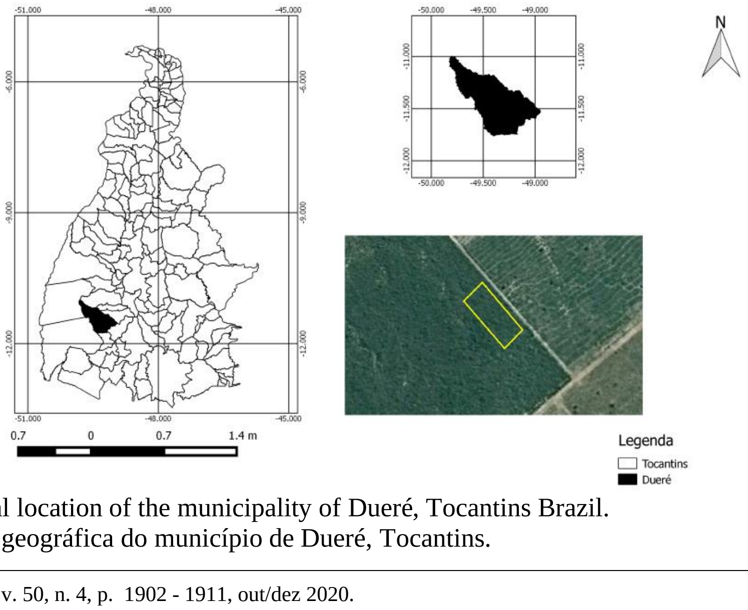

Figure 1. Geographical location of the municipality of Dueré, Tocantins Brazil.
Figura 1. Localização geográfica do município de Dueré, Tocantins.

The species evaluated were *Anacardium humile* A. St.-Hil. (cajuzinho), *Palicourea rigida* Kunth (bate-caixa), *Terminalia glabrescens* Mart. (mirindiba), *Vatairea macrocarpa* (Benth) Ducke (angelim-amargoso), and *Xylopia aromatica* (Lam.) Mart. (pimenta-de-macaco), the choice of species was defined according to their residual distribution in the collection area.

Sampling

The logs collected in the field were processed to make ten specimens, selected homogeneously in each of the five species under study, totaling 50 specimens with dimensions of approximately 2.0 x 2.0 x 5.0 cm (width x thickness x length). For the study, two treatments were performed, being ten specimens for each species evaluated with five repetitions for each heating speed (500 and 550 °C), respectively. The same bodies of evidence were used for all tests performed in this study.

Basic density of wood

The basic density of the wood was determined by the method of immersion in water, according to the ASTM D-2395 standard of the American Society for Testing and Materials (ASTM) (2005).

Wood pyrolysis

Before the carbonization process, the specimens were dried in an oven at 103 °C ± 2 °C. The samples were carbonized in an electric muffle furnace with programmed final temperature control and adapted to recover condensable volatile materials. The temperature control was carried out at two different heating speeds (Table 1).

Table 1. Temperature and time of carbonization according to carbonization heating speed.
Tabela 1**.** Temperatura e tempo de carbonização em função da marcha de carbonização.

Heating Speed	Temperature (°C)							Heat Index (°C/min)	Total Time (h)
	150	200	250	350	450	500	550		
1	1h	1h	1h30	1h30	1h	1h	-	1.2	7h
2	1h	1h	1h30	1h30	30min	30min	30min	1.4	6h30

Subtitle: Adapted from Silva *et al*. (2018).

Yield in pyrolytic liquor and non-condensable gases

The recovery of condensable gases was carried out through an adaptation to the muffle furnace that allows the gases to pass through a condenser to liquefy them in a compound of acetic acid, formic acid, methanol and tar called pyroligneous liquor.

Through the difference between the total gravimetric yield in coal and the total yield in pyroligneous liquor, the total yield in non-condensable gases was obtained.

Total gravimetric yield of charcoal

The total gravimetric yield is the percentage relationship between the dry mass of the coal and the dry mass of the wood, obtained by weighing on an analytical balance.

Charcoal apparent density

The apparent density of coal was determined based on the standard of the Brazilian Association of Technical Standards - ABNT NBR 9156 (1985).

Immediate Chemical Analysis (ICA)

The immediate chemical composition was carried out following ASTM D 1762-84 American Society for Testing and Materials, (2007) in which the contents of volatile material, fixed carbon, and coal ash were determined.

Determination of the calorific value of charcoal

The calorific value of coal was calculated according to Vale *et al.* (2002).

$$PCS = 4934{,}43 + 33{,}27 * CF$$

Where: SHV = superior heat value of coal ($kcal.kg^{-1}$); FC = fixed carbon content (%).

Statistical analysis of data

In the evaluation of the experiment, a completely randomized experimental design was used in a 5 x 2 factorial scheme, with five species and two heating speeds. First, the normality test was performed. After its verification, the analysis of variances (ANOVA) was applied. Observing significant differences between the treatments, the Tukey test was used to compare the means at a 5% probability level.

RESULTS

Basic density of wood

The basic density showed significant differences (p≥0.05) between the species evaluated and that, among them, *Terminalia glabrescens* had the highest average value (0.74 g.cm^{-3}) and *Xylopia aromatica* the lowest value (0.54 g.cm^{-3}) (Table 2).

Table 2. Mean values of basic wood density of the species *Anacardium humile, Palicourea rigida, Terminalia glabrescens, Vatairea macrocarpa* and *Xylopia aromatica*.
Tabela 2. Valores médios de densidade básica da madeira das espécies *Anacardium humile, Palicourea rigida, Terminalia glabrescens, Vatairea macrocarpa* e *Xylopia aromatica*.

Species	Bd (g.cm^{-3})	VC (%)	F
Anacardium humile	0.49 d	4.86	
Palicourea rigida	0.58 c	12.60	
Terminalia glabrescens	0.74 a	2.00	63.21*
Vatairea macrocarpa	0.65 b	3.03	
Xylopia aromatica	0.54 c	2.40	

Subtitle: Averages followed by the same lower case letter in the column do not differ statistically in the Tukey test (p ≥ 0.05). VC = Variation Coefficient. * significant at 5%.

Wood pyrolysis

The highest total gravimetric yield on coal was *Terminalia glabrescens* (36.24%) and the lowest was *Xylopia aromatica* (29.41%), at the heating speed of 500 °C. At 550 °C, the highest total value was also that of *Terminalia glabrescens* (34.61%) and the lowest value was also for *Xylopia aromatica* (28.84%) (Table 3).

Regarding the yield in condensable gases, the highest total value among the five species was observed for *Xylopia aromatica* (53.64% and 54.69%) and the lowest was for *Palicourea rigida* (41.57% and 43.30 %), at the heating speeds of 500 °C and 550 °C, respectively.

It is observed that, among the five species, the one with the highest total yield in non-condensable gases was *Palicourea rigida* (23.94% and 24.01%) and the lowest was *Xylopia aromatica* (16.95% and 18.47%), for gears with final carbonization temperature of 500 °C and 550 °C.

Table 3. Total values of the yield of charcoal (YC), in condensable (YL) and non-condensable (YNNC) gases of the species *Anacardium humile, Palicourea rigida, Terminalia glabrescens, Vatairea macrocarpa,* and *Xylopia aromatica*.
Tabela 1. Valores totais do rendimento do carvão vegetal (RTC), em gases condensáveis (RGC) e não condensáveis (RGNC) das espécies *Anacardium humile, Palicourea rigida, Terminalia glabrescens, Vatairea macrocarpa* e *Xylopia aromatica*.

Species	Parameters	Heating speeds	
		500 °C	550 °C
Anacardium humile	YC (%)	34.78	33.33
	YL (%)	44.60	44.74
	YNCG (%)	20.62	21.93
Palicourea rigida	YC (%)	34.48	32.69
	YL (%)	41.57	43.30
	YNCG (%)	23.95	24.01
Terminalia glabrescens	YC (%)	36.25	34.61
	YL (%)	42.00	44.14
	YNCG (%)	21.75	21.25
Vatairea macrocarpa	YC (%)	31.34	33.84
	YL (%)	46.32	48.38
	YNCG (%)	22.34	17.78
Xylopia aromatica	YC (%)	29.41	28.84
	YL (%)	53.64	52.69
	YNCG (%)	16.95	18.47

Subtitle: YC coal = Gravimetric yield of charcoal; YL = Yield of Condensable Gases / pyroligneous liquor; YNCG = Yield of Non-Condensable Gases.

Charcoal quality

Charcoal apparent density

Significant statistical differences were observed between species, but there were no significant differences between heating speeds and there was no interaction between the two factors at a 5% probability concerning the apparent density of charcoal. Among the five species, the highest average was for *Terminalia glabrescens* (0.66 $g.cm^{-3}$) and the lowest for *Anacardium humile* (0.38 $g.cm^{-3}$). The heating speed that revealed the highest average between the two gears studied was 550 °C (0.53 $g.cm^{-3}$) (Table 4). The basic density of wood showed a positive correlation with the apparent density of charcoal (r = 0.87).

Table 4. Average values of the apparent density of coal (Ad) of the species *Anacardium humile, Palicourea rigida, Terminalia glabrescens, Vatairea macrocarpa*, and *Xylopia aromatica*.
Tabela 2. Valores médios da densidade aparente do carvão (Da) das espécies *Anacardium humile, Palicourea rigida, Terminalia glabrescens, Vatairea macrocarpa* e *Xylopia aromatica*.

Species	**Ad ($g.cm^{-3}$)**	**VC (%)**	**F**
Anacardium humile	0.38 d	12.00	
Palicourea rigida	0.49 c	17.61	
Terminalia glabrescens	0.66 a	6.50	37.84*
Vatairea macrocarpa	0.58 b	3.80	
Xylopia aromatica	0.41 d	5.80	
Heating speeds	**Ad ($g.cm^{-3}$)**	**VC (%)**	**F**
500 °C	0.51 a	29.07	3.16^{ns}
550 °C	0.53 a	25.91	
Interaction	**Ad ($g.cm^{-3}$)**	**VC (%)**	**F**
Species x Heating speed	-	-	0.95^{ns}

Subtitle: Averages followed by the same lowercase letter do not differ statistically (Tukey's test - P≥0.05). VC = Variation Coefficient. * significant at 5% level. ^{ns} = not significant.

Immediate Chemical Analysis (ICA)

Regarding the volatile matter content, there were significant differences between the five species, the heating speeds, and the interaction of the two factors as the F test was significant at a 5% probability level. The highest average found was for *Anacardium humile* (30.18%) and the lowest was for *Vatairea macrocarpa* (21.21%), at the 500 °C heating speed. At the 550 °C heating speed, the highest average obtained was for *Palicourea rigida* (24.44%) and the lowest for *Anacardium humile* (18.53%) (Table 5).

Significant statistical differences (p≥0.05) were observed between species, the heating speeds, and the interaction of the two factors because the species had suffered the effect of the final carbonization temperature for the fixed carbon content. The highest mean value observed was for *Vatairea macrocarpa* (75.26%) and the lowest for *Anacardium humile* (59.22%), at the 500 °C heating speed. At the 550 °C heating speed, the highest average was for *Xylopia aromatica* (77.55%) and the lowest for *Palicourea rigida* (68.84%).

Significant statistical differences can be observed between the five species, the heating speeds, and the interaction between the two factors because the species were affected by the heating speeds for the calorific power of the coal at the level of 5% probability. The highest average obtained was for *Vatairea macrocarpa* (7438.21 $kcal.kg^{-1}$) and the lowest for *Anacardium humile* (6904.62 $kcal.kg^{-1}$) with a final carbonization temperature of 500 °C. At the heating speed of 550 °C, the highest mean value found was for *Terminalia glabrescens* (7542.66 $kcal.kg^{-1}$) and the lowest was also for *Anacardium humile* (7224.82 $kcal.kg^{-1}$).

Table 5. Average values of characteristics evaluated in the coal, as well as the multiple comparison test performed for the species *Anacardium humile, Palicourea rigida, Terminalia glabrescens, Vatairea macrocarpa*, and *Xylopia aromatica*.
Tabela 3. Valores médios das características avaliadas no carvão, bem como o teste de comparação múltipla realizado para as espécies *Anacardium humile, Palicourea rigida, Terminalia glabrescens, Vatairea macrocarpa* e *Xylopia aromatica*.

Parameters	Species	Heating speed				F
		500 °C	VC (%)	550 °C	VC (%)	
MV (%)	*Anacardium humile*	30.18 aA	10.8	18.53 bB	7.93	12.85*
	Palicourea rigida	25.90 aBC	1.68	24.44 a A	9.33	
	Terminalia glabrescens	25.81 aBC	8.83	21.45 bAB	8.81	
	Vatairea macrocarpa	21.21 aC	5.40	23.85 aA	8.40	
	Xylopia aromatica	28.41 aAB	6.23	20.09 bA	5.40	
FC (%)	*Anacardium humile*	59.22 bC	5.53	70.40 aB	2.05	5.02*
	Palicourea rigida	70.74 aB	0.63	68.84 aB	3.30	
	Terminalia glabrescens	73.27 bAB	3.01	75.58 aA	2.38	
	Vatairea macrocarpa	75.26 aA	1.76	75.16 aA	2.56	
	Xylopia aromatica	70.99 bB	2.42	77.55 A	7.70	
HCV (kcal.kg^{-1})	*Anacardium humile*	6904.62 bC	1.58	7224.82 aC	0.65	5.02*
	Palicourea rigida	7288.12 aB	0.20	7276.61 aC	1.06	
	Terminalia glabrescens	7372.15 bAB	0.99	7542.66 aA	0.77	
	Vatairea macrocarpa	7438.21 aA	0.59	7448.93 bB	0.86	
	Xylopia aromatica	7296.22 bB	0.78	7434.90 aB	0.57	

Subtitle: Averages followed by the same lowercase letter on the line and the same UPPERCASE letter in the column do not differ statistically (Tukey's test - P≥0.05). VC = Variation Coefficient. * significant at 5%.

Regarding the ash content, significant statistical differences can be observed between the studied species, between the heating speeds, without interaction between the factors. The ash content showed a high variation coefficient for the species *Palicourea rigida* and *Vatairea macrocarpa.* The highest average obtained was for the species *Anacardium humile* (11.61%) and the lowest average was for *Vatairea macrocarpa* (0.55%). The carbonization rate with the highest average was 550 °C (4.01%) (Table 6).

Table 6. Average values ash content for species *Anacardium humile*, *Palicourea rigida*, *Terminalia glabrescens*, *Vatairea macrocarpa,* and *Xylopia aromatica.*
Tabela 6. Valores médios teor de cinzas para as espécies *Anacardium humile*, *Palicourea rigida*, *Terminalia glabrescens*, *Vatairea macrocarpa* e *Xylopia aromatica*.

Species	Ashes (%)	VC (%)	F
Anacardium humile	11.61 a	9.19	504.96*
Palicourea rigida	4.25 b	22.32	
Terminalia glabrescens	0.96 c	9.65	
Vatairea macrocarpa	0.55 e	20;59	
Xylopia aromatica	0.67 d	14.67	
Heating speeds	**Ashes (%)**	**VC (%)**	**F**
500 °C	3.20 b	122.66	13.60*
550 °C	4.01 a	117.52	
Interaction	**Ashes (%)**	**VC (%)**	**F**
Species x Heating speeds	-	-	0.308^{ns}

Subtitle: Averages followed by the same lowercase letter do not differ statistically (Tukey's test - P≥0.05). VC = Variation Coefficient. * significant at 5%.· ^{ns} = not significant.

DISCUSSION

Basic density of wood

The averages of basic wood density (Table 2) were compared with the literature and the values are close to what was observed in this study. Lorenzi (2016) found average values for basic density of *Palicourea rigida* wood, *Terminalia glabrescens, Vatairea macrocarpa* and *Xylopia aromatica* equal to 0.43 g.cm^{-3}, 0.60 g.cm^{-3}, 0.88 g.cm^{-3} and 0.54 g.cm^{-3}, respectively.

The species *Anacardium humile* and *Xylopia aromatica* have low density (<0.55 g.cm^{-3}), whereas *Palicourea rigida* and *Vatairea macrocarpa* are medium density (> 0.55 g.cm^{-3}) and *Terminalia glabrescens* is considered to be of high density (> 0.73 g.cm^{-3}). According to Silveira *et al.* (2013), the woods are classified as: light or low density wood (<0.55 g.cm^{-3}), medium density (between 0.55 and 0.72 g.cm^{-3}), and heavy wood or high density (> 0.73 g.cm^{-3}).

According to Neves *et al.* (2011), when referring to the quality of the charcoal, a high basic density of the wood is desirable because, the higher the basic density of the wood, the greater the energy density of charcoal.

Wood pyrolysis

Total charcoal yields were affected by the carbonization march (Table 3), with a decrease in charcoal yield as the time and final temperature of carbonization increased, except for the coal of the species *Vatairea macrocarpa*, which presented a higher percentage at the heating speed of 550 °C. Elyounssi *et al.* (2010) and Vieira *et al*. (2013), reported that process parameters such as temperature influence the gravimetric yield and, the higher the final temperature, the lower the mass yield, due to the higher degree of volatilization of organic matter, which results in lower yield in coal and increase in pyroligneous liquid yields.

Costa *et al.* (2014) characterized five species from the Cerrado and denoted average values for gravimetric yield ranging from 30.88 to 34.39%. In a study on the quality of the charcoal of *Qualea parviflora* species from the Cerrado, Protásio *et al*. (2011) found an average charcoal yield of 34.60%. The values described by the authors were close to those found in this study for the five species.

The total yield in pyroligneous liquor increased with the increase of the final carbonization temperature for the species *Anacardium humile*, *Palicourea rigida*, *Terminalia glabrescens* and *Vatairea macrocarpa*. The opposite result was found in the yield in non-condensable gases, which decreased when the final carbonization temperature was increased in the pyrolysis process of the mentioned woods. A possible explanation for this fact is that due to the increase in the final carbonization temperature, there was a decrease in the total gravimetric yield in coal and, consequently, there was an increase in the total yield in pyrolytic liquid and a decrease in the total yield in non-condensable gases because they are directly correlated. According to Vieira *et al.* (2013), the higher the degree of wood degradation in the carbonization process, the lower the charcoal yield, the higher the liquor yield and the lower the non-condensable gas yield.

In a study carried out to determine the quality of *E. pellita* charcoal, Oliveira *et al.* (2010) observed yield in liquor of 58.98% and yield in non-condensable gases of 9.93% at the heating speed of 500 °C. At 550 °C, the average values were 58.01% for yield in liquor and 11.86% for yield in non-condensable gases. The values for liquor yield were higher and the yield in non-condensable gases was lower than that observed in this study for the heating speeds of 500 °C and 550 °C.

Charcoal quality

Charcoal apparent density

The averages obtained for the five Cerrado species in this study for apparent coal density were considered higher than what was observed in the literature. In a study by Costa *et al.* (2014), the authors observed average values between 0.25 to 0.47 g.cm^{-3} of apparent coal density for five native Cerrado species. Vale *et al.* (2010) obtained average values for apparent coal density of five native Cerrado species ranging from 0.28 to 0.43 g.cm^{-3}.

The apparent density of the charcoal showed a positive correlation with the basic density of the wood. This behavior was expected due to the apparent density of the charcoal being directly proportional to the basic density of the wood. Vale *et al.* (2010) state that, the higher the density of the wood, the denser the charcoal will be, the greater the energy produced per unit volume, and the lower the costs associated with transportation.

According to Oliveira *et al.* (2010), the quality of charcoal depends on the apparent density of the charcoal. The five species evaluated in this study showed potential for charcoal production when analyzing their apparent density, as they were considered high.

Immediate Chemical Analysis (ICA)

There was a reduction in volatile materials with an increase in the final carbonization temperature (Table 5), as according to Oliveira *et al.* (2010) and Figueiredo *et al.* (2018), the temperature and the heating rate are parameters that interfere directly in the percentage of volatiles in the materials because, with the increase in temperature, the gas expansion occurs, due to this the greater degradation of the materials, reducing the number of volatile materials present in the charcoal.

The state of São Paulo has a Premium Seal for charcoal, promulgated by Resolution SAA-40 of December 14, 2015, which implies some minimum standards for the produced coal to acquire this seal. Some aspects of this resolution are related to technical levels. The content of volatile materials (VM) has to be less than 23.50% (SÃO PAULO, 2015). Only the species *Vatairea macrocarpa* was below the indicated value.

Protásio *et al.* (2011) studied the charcoal of the native species of the Cerrado *Qualea parviflora* and obtained an average value for the volatile matter content of 21.18%. Costa *et al.* (2014) observed average values for volatile material content in an interval between 14.4 to 20.0% for five native species of the Cerrado biome.

These values were considered lower than the levels of volatile matter found in this study for the five species evaluated.

The fixed carbon content for the species evaluated (Table 5) was considered lower than those obtained by Costas *et al.* (2014). In a study carried out to characterize the coal of five species in the Cerrado, the average values ranged from 77.2 to 81% for the fixed carbon content. Protásio *et al.* (2011) found an average value of 75.89% for the fixed carbon content of Qualea parviflora coal. The species *Terminalia glabrescens*, *Vatairea macrocarpa* and *Xylopia aromatica* presented values close to those observed by the author.

Oliveira *et al.* (2010) evaluated the final carbonization temperatures of 450 °C, 500 °C and 550 °C in *Eucalyptus pellita* and observed that, with an increase in the final carbonization temperature, there was an increase in the fixed carbon content. The authors concluded that the increase in final carbonization temperature causes a decrease in the gravimetric yield in coal, an increase in the production of gaseous products, and an increase in the concentration of fixed carbon in the solid fraction, confirming the results found in the present study.

Fuels with high levels of fixed carbon are preferable for steel use, due to thermal stability and high energy power (NEVES *et al.*, 2011). The fixed carbon values in this study follow Resolution SAA-40 only for the species *Terminalia glabrescens, Vatairea macrocarpa* and *Xylopia aromatica.* It determines values considered ideal for quality coal: fixed carbon content above 73% (SÃO PAULO, 2015).

When the final carbonization temperature increased, there was an increase in the calorific value of the coal of the five studied species (Table 5). Silva *et al.* (2018) reported that a possible explanation for this fact may be because the fixed carbon content increases with an increase in the final carbonization temperature.

Protásio *et al.* (2011) observed an average calorific value of 7259.10 kcal.kg^{-1} for the coal of *Qualea parviflora* species from the Cerrado. Costa *et al.* (2014), found average values of calorific power between 7135 and 7730 kcal.kg^{-1} for five species from the Cerrado. These values were close to those observed for the studied Cerrado species.

Oliveira *et al.* (2010) denoted an average of 8237 kcal.kg^{-1} at the heating speed of 500 °C and 8172 kcal.kg^{-1} at 550 °C for *Eucalyptus pellita.* The values obtained by the authors were higher than those observed in this study for the heating speeds of 500 °C and 550 °C, respectively.

The ash contents in this study were considered acceptable for the species *Terminalia glabrescens, Vatairea macrocarpa* and *Xylopia aromatica*, as they presented values below 1.5%, but the species *Anacardium humile* and *Palicourea rigida* had average values above acceptable (Table 6), according to Resolution SAA-40, where it is determined that the acceptable value for ash content is less than 1.5% (SÃO PAULO, 2015). The ash content directly influences the calorific value of the fuel, showing a negative correlation, as the ash does not participate in the combustion process (BRAND, 2010).

The high ash content obtained for Anacardium humile coal (11.61%) explains its lower fixed carbon content (64.81%) and consequently, lower calorific value (7064.72 kcal.kg^{-1}), through low basic density of the wood and apparent density of coal equal to 0.49 and 0.38 g.cm^{-3}, respectively.

CONCLUSION

Given the above, it is concluded that:

- The basic density of the wood presented acceptable values for the production of charcoal for species *Palicourea rigida*, *Terminalia glabrescens* and *Vatairea macrocarpa* because the averages varied (0.55 to 0.73 g.cm^{-3}) from medium to high density.
- The gravimetric yield of the coal and apparent density of the coal produced from the species *Terminalia glabrescens* (0.66 g.cm^{-3} and 36.25%) and *Vatairea macrocarpa* (0.58 g.cm^{-3} and 31.24%) obtained acceptable average values for charcoal production.
- The yield on condensable gases and the yield on non-condensable gases were influenced by the heating speeds as well as the content of volatile materials.
- The content of volatile materials for the species *Anacardium humile*, *Palicourea rigida*, *Terminalia glabrescens* and *Xylopia aromatica* did not present average values within the recommended for charcoal production because they are superior to 23.5%.
- The fixed carbon content, ash and the calorific value of the species *Terminalia glabrescens*, *Vatairea macrocarpa,* and *Xylopia aromatica*, presented average values above 73% and below 1.5%, being acceptable values for the production of coal.
- The *Vatairea macrocarpa* species and the heating speed with a final temperature of 550 °C are recommended for the production of charcoal because it had a lower content of volatile materials, greater calorific value, and higher content of fixed carbon in the coal.

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