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COMBUSTION OF BIOMASS AND CHARCOAL MADE FROM BABASSU NUTSHELL

Keywords:
Alternative biomass
Renewable energy
Thermal analysis
Ignition

ABSTRACT: In recent years, studies have examined the use of lignocellulosic wastes for energy generation. However, there is a lack of information on the combustibility of the residual biomass, especially the bark and charcoal of babassu nut. In this study, thermogravimetric analysis (TGA), differential thermal analysis (DTA) and differential scanning calorimetry (DSC) were used to achieve the following objectives: to evaluate the combustion of the residual biomass from the babassu nut; to evaluate the combustion of charcoal produced from this biomass, considering different final carbonization temperatures; and to determine the effect of the final carbonization temperature on the thermal stability of charcoal and on its performance in combustion. Thermal analyses were performed in synthetic air. In order to evaluate the characteristics of charcoal combustion and fresh biomass, the ignition temperature (T_i), the burnout temperature (T_f), characteristic combustion index (S), ignition index (D_i), time corresponding to the maximum combustion rate (t_p), and ignition time (t_{ig}) were considered. The combustion of the babassu nutshell occurred in three phases and it was observed that this lignocellulosic material is suitable for the direct generation of heat. The increase in the final carbonization temperature caused an increase in the ignition temperature, as well as in the burnout temperature, the ignition time and the time corresponding to the maximum combustion rate. The results indicate that the increase in the carbonization temperature causes a decrease in combustion reactivity and, consequently, the charcoals produced at lower temperatures are easier to ignite and exhibit better performance in ignition.

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COMBUSTÃO DA BIOMASSA E DO CARVÃO VEGETAL DA CASCA DO COCO BABAÇU

Palavras chave:
Biomassa alternativa
Energia renovável
Análises térmicas
Ignição

RESUMO: Nos últimos anos, pesquisadores têm analisado o uso de resíduos lignocelulósicos para geração de energia. No entanto, há uma falta de informação sobre a combustibilidade da biomassa residual, especialmente a casca e o carvão vegetal do coco babaçu. Neste estudo foram utilizadas as análises termogravimétricas (TGA), térmica diferencial (DTA) e de calorimetria exploratória diferencial (DSC) para: avaliar a combustão da biomassa residual do coco babaçu; avaliar a combustão do carvão vegetal produzido a partir dessa biomassa, considerando diferentes temperaturas finais de carbonização; e verificar o efeito da temperatura final de carbonização na estabilidade térmica do carvão vegetal e no seu desempenho na combustão. As análises térmicas foram realizadas em atmosfera de ar sintético. Para avaliar as características da combustão do carvão vegetal e da biomassa in natura foi considerada a temperatura de ignição (Ti), a temperatura final da combustão (Tf), o índice característico da combustão (S), o índice de ignição (Di), o tempo correspondente à máxima taxa de combustão (tp) e o tempo de ignição (tig). A combustão da casca do coco babaçu ocorreu em três fases distintas e observou-se que esse material lignocelulósico apresenta aptidão para a produção direta de calor. O aumento da temperatura final de carbonização causou um aumento da temperatura de ignição, da temperatura final da combustão, do tempo de ignição e do tempo correspondente à máxima taxa de combustão. Os resultados indicam que o aumento da temperatura de carbonização causa uma diminuição da intensidade da combustão e, consequentemente, os carvões produzidos em temperaturas mais baixas são mais fáceis de inflamar e apresentam melhor desempenho na ignição.

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INTRODUCTION

Traditionally, wood is used as a bioenergy source by either direct complete combustion or the conversion into various biofuels by means of specific routes. However, in recent years, researchers have examined the use of lignocellulosic wastes for this purpose, because those plant materials also feature organic compounds that can be oxidized and generate energy in a sustainable and efficient manner. According to Sain et al. (2015), maize, wheat, rice, and sugarcane are the four agricultural crops with the most production in the world as well as largest area under cultivation.

Therefore, studies on the use of alternatives biomass, for example, the babassu nut waste, have great potential to be used for energy generation (PROTÁSIO et al., 2014a, 2014b, 2014c; REIS et al., 2015). Babassu nutshell showed a high basic density and a suitable lignin content for the sustainable production of bioenergy and charcoal (PROTÁSIO et al., 2014a). However, there is a lack of information on the combustibility of residual biomass, especially the bark and charcoal of babassu nut.

The babassu palm is an evergreen, heliophytic and pioneer tree and it is native to Brazil and other countries in the Americas. It references three distinct genera of the family Arecaceae: *Scheelea, Attalea* and *Orbignya*, but the species *Orbignya phalerata* Mart. is the most common and widespread (TEIXEIRA, 2008). Porro et al. (2011) comment that the babassu nuts are grown for the removal of almonds for the manufacture of vegetable oil, being it's shell the main waste produced in the process.

The fruit is composed of 12% epicarp, 23% mesocarp, and 58% endocarp or core material, with 93% of the coconut considered waste (shell). Therefore, each ton of babassu has 930 kg of biomass residues that can be allocated to the direct generation of heat in the industrial or residential systems as well as for the production of charcoal (EMMERICH and LUENGO, 1996; DIAS et al., 2012). Regarding the availability of biomass from babassu for bioenergy use, Teixeira (2008) estimated a potential exceeding six million tons per year. Maranhão is the Brazilian state with the highest potential for utilization of energy from babassu biomass.

In addition, the charcoal of babassu nutshell has high values of apparent density and energy density, possesses chemical and energetic properties suitable for steel use, and can be considered as a potential replacement of wood charcoal (SILVA et al., 1986; EMMERICH; LUENGO, 1996; PROTÁSIO et al., 2014b). The charcoal from babassu coconut can be used for direct heat generation in other industrial segments; however, their combustibility or combustion performance should be studied.

Despite the known possibility of using biomass of babassu nut and charcoal produced for direct energy generation there is a shortage of information related to their combustibility. It is known that among the various processes for converting biomass into energy, direct combustion is a more commercially widespread process and it is the oldest, simplest, and most noteworthy way of obtaining heat.

Thermal analysis of thermogravimetric (TGA), differential thermal (DTA) and differential scanning calorimetry (DSC) are techniques widely used to evaluate the oxidation process or the biomass combustibility. They have been used to evaluate the decomposition of the organic components of biomass and charcoal. The objective is to verify the type of reaction (endothermic or exothermic), evaluating the performance of the oxidation of materials during the ignition phase (KAI et al., 2011; LIU et al., 2013; MAGDZIARZ; WILK, 2013; LÓPEZ-GONZÁLEZ et al., 2013).

In this study, thermogravimetric analysis (TGA), differential thermal analysis (DTA) and differential scanning calorimetry (DSC) were used with the following aims: to assess the combustion of the residual biomass babassu nut; to evaluate the combustion of charcoal produced from such biomass while considering different final temperatures of carbonization; and to determine the effect of the final carbonization temperature on the thermal stability of charcoal and its performance in combustion.

MATERIAL AND METHODS

The three constituent layers of the babassu nut, i.e. the epicarp, mesocarp and the endocarp (Figure 1), were used together.

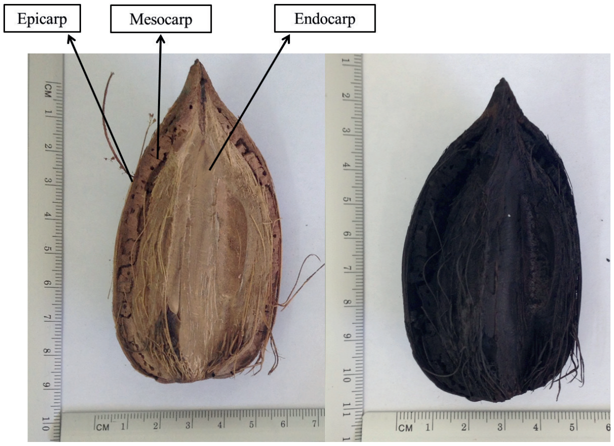

FIGURE 1 Fragments of babassu used for carbonization and charcoal obtained from the final temperature of 450°C.

The material was collected in the rural municipality of Sítio Novo do Tocantins, Tocantins State. Local communities obtain it from extractive exploitation. Babassu nutshell comes from manual breaking. The fresh biomass was processed in a hammer mill, homogenized and classified in sieves with 40, 60 and 200-mesh.

Carbonization was performed in an electric furnace (muffle), with about 500 g of babassu nutshell used in each test. The samples were previously dried at 103 ± 2°C. The initial temperature of the furnace was 100°C and the final temperatures of 450°C, 550°C, 650°C, 750°C and 850°C were tested, considering a heating rate of 1.67°C·min^{-1}. The temperature of the furnace remained stable for 30 minutes during the final phase. The total time of carbonization was 4 h, 5 h, 6 h, 7 h, and 8 h at the temperatures of 450°C, 550°C, 650°C, 750°C and 850°C, respectively.

For charcoal derived from babassu nutshell and for each final temperature, four replications were performed. The procedure used in the laboratory for carbonization is similar to that found in the literature for wood (ASSIS et al., 2012; PROTÁSIO et al., 2013).

The charcoal was duly crushed and classified into sieves of 40, 60 and 200-mesh, considering the four composite samples repetitions to perform the thermal analysis (DSC, TGA and DTA). Charcoal samples with particle size fraction that passed through 60-mesh sieve and were retained on the 200-mesh sieve were used for thermogravimetric analysis (TGA), differential thermal analysis (DTA) and differential scanning calorimetry (DSC). The thermal analysis (TGA and DTA) was performed on a synthetic air atmosphere (flow rate of 100 ml min^{-1}) with SDT 2960 Simultaneous DTA-TGA units from TA Instruments, using 6 mg of samples and a temperature that ranged from room conditions to 1,000°C, with a heating rate of 10°C·min^{-1}.

For fresh biomass or babassu nutshell, the thermal analysis was performed up to approximately 550°C. From this temperature onwards there is no more potential for oxidizing organic matter. Using the first derivative of the TGA curve (DTG) it was possible to identify the rate of weight loss per minute and the characteristic stages of combustion of fresh biomass and also for charcoal obtained.

The differential scanning calorimetry test was conducted only for fresh biomass, using the DSC 2010 of TA Instruments equipment. Samples of 2 mg were placed in aluminum containers. A standard sample used the empty container. The thermograms were obtained from room temperature to 550°C, with a heating rate of 10°C min^{-1} and a synthetic air flow of 70 mL·min^{-1}.

The ignition temperature (T_i), the burnout temperature (T_f), the characteristic combustion index (S), the ignition index (D_i), the time corresponding to the maximum rate combustion (t_p), the ignition time (t_{ig}), the maximum combustion rate and the average rate of combustion were considered.

In this study, the ignition temperature (T_i) was defined as the temperature at which the combustion rate increased to 1 wt·%·min^{-1} at the start of a major combustion process. The burnout temperature (T_f) was defined as the temperature at which the combustion rate decreased to 1 wt·%·min^{-1} at the end of a combustion process (MOON et al., 2013; WANG et al., 2011; WANG et al., 2012).

The combustion characteristic index (S) was obtained by Equation [1] (QIAN et al., 2012; LI et al., 2013; LIU et al., 2013; MOON et al., 2013), where: $(dm/dt)_{max}$ is the maximum combustion rate (%·min^{-1}); $(dm/dt)_{average}$ is the average rate of combustion; T_i is the ignition temperature (°C), T_f is the burnout temperature (°C).

$$S = \frac{\left(\frac{dm}{dt}\right)max\left(\frac{dm}{dt}\right)average}{Ti^2 \times Tf} \qquad [1]$$

The ratio of ignition (Di) was obtained by Equation [2] (XIANG-GU et al., 2006), where: $(dm/dt)_{max}$ is the maximum combustion rate (%·min^{-1}); t_p is the corresponding to the maximum combustion rate (min) and t_{ig} time is the time from ignition (min.).

$$Di = \frac{\left(\frac{dm}{dt}\right)max}{tp \ x \ tig} \qquad [2]$$

In order to better understand the combustion of fresh biomass and charcoal, chemical analysis was performed to quantify the levels of volatile materials (VM) and fixed carbon (FC) according to (ASTM D 1762, 1984).

RESULTS AND DISCUSSION

Fresh biomass

It is observed that the ignition temperature (T_i) of babassu nutshell was 240.35°C and the burnout temperature (T_f) was 433.86°C (Figure 2). These temperatures are considerably lower than those for charcoal (SAHU et al., 2010), because the relative volatile/fixed carbon from the bark of the babassu nut is high (3.95). Thus it has been observed that the ignition time of the fresh biomass was low (22.8 min), the maximum and mean combustion rate were high and equal to 24.2246%·min^{-1} and 1.8498%·min^{-1}, respectively.

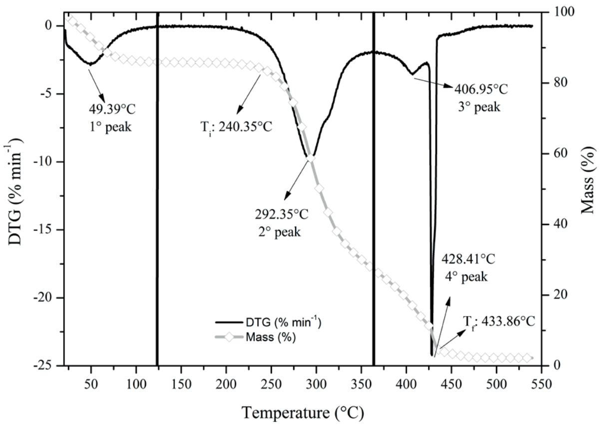

FIGURE 2 A curves and DTG combustion of fresh babassu nutshell.

The combustion characteristic index (S) and the index of ignition (D_i) were also high: 17.88×10^7 %^{2} / (min^2 °C^3) and 25.74×10^3 % min^{-3}, respectively, and demonstrate the performance of the babassu nutshell during the combustion process. Sahu et al. (2010) evaluated the ignition of the pyrolyzed rice husk at 450°C and found D_i rate of 3.54×10^3 % min^{-3}, lower than what was found for the fresh biomass babassu nut. This result demonstrates the ease of ignition of the studied lignocellulosic material compared to the charcoal of rice husk.

Three stages of thermal degradation of fresh biomass were observed. The first stage occurs from room temperature to 125°C and drying of the sample corresponds to a peak weight loss at 49.39°C. In this phase the mass loss is related to the moisture content of 14.05%.

The second stage, the devolatilization of the major components of biomass (LI et al., 2013), begins immediately after a period of thermal stability and extends up to about 360°C, with a thermal degradation peak at 292.35°C. A similar result was observed by Fernandes et al. (2013) to partially dried banana leaves. The authors observed a peak in the devolatilization step at 300°C. Magdziarz and Wilk (2013), analyzing wood pellets, observed that this phase lasted until 350°C. López-González et al. (2013) observed that the degradation peak of the *Eucalyptus* occurs at 290°C by thermogravimetric analysis in synthetic air atmosphere.

The devolatilization phase corresponding to the degradation of hemicelluloses, cellulose and part of lignin results in the release of volatiles and ignition (homogeneous combustion) and leads to the formation of the charcoal (MAGDZIARZ; WILK, 2013; KAI et al., 2011; FERNANDES et al, 2013). Thus, the rate of weight loss of the sample was high, since carbohydrates have low resistance to thermal degradation. The weight loss at this stage was 58%. According to López-González et al. (2013), between the temperatures of 180°C and 388°C, rapid degradation of hemicelluloses and cellulose occurs because the sugars in plant biomass degrade at low temperatures, confirming the results found for the shell of the babassu nut. The high cellulose content promotes greater devolatilization and increases the rate of thermal decomposition at lower temperatures (KAI et al., 2011).

During the third stage, there is a narrow peak at 428.41°C that relates to the decomposition of residual lignin oxidation and burning of fixed carbon formed on the second and third phases. This stage corresponds to the homogeneous combustion of released gases by the decomposition of lignin and heterogeneous combustion of solid carbon (MAGDZIARZ; WILK, 2013; MOON et al., 2013; KAI et al., 2011; FANG et al., 2006).

Therefore, in this phase the mass loss was lower than the previous stage, corresponding to 25.79%. We observed also a small shoulder at 406.95°C corresponding to the transition from the combustion of cellulose and lignin (REH et al., 1986). Lignin is the major contributor at this stage. It is the primary biomolecule responsible for the formation of charcoal due to its higher thermal stability compared to cellulose and hemicelluloses. The lignin macromolecule presents C-C linkages between phenylpropane units, which result in thermal stability of its predominantly aromatic structure (KAI et al., 2011; SANCHEZ-SILVA et al., 2012; GANI; NARUSE, 2007; YANG et al., 2007; SHARMA et al., 2004).

Kai et al. (2011) observed that combustion of lignin occurs in a wide temperature range (152°C to 700°C), but the rate of weight loss at lower temperatures is minimal (LÓPEZ-GONZÁLEZ et al., 2013). Thus, the solid fraction resulting from combustion of this macromolecule is approximately 9% higher than the other structural components of plant biomass (KAI et al., 2011). Furthermore, the fixed carbon is the fraction of the fuel that burns in the solid state and, thus, provides major thermal stability and less weight loss of the biomass during of the combustion (PROTÁSIO et al., 2013).

The inorganic matter (ash) from the burning babassu is approximately 2%. This value can be considered low compared to coal widely used around the world for the generation of electricity in thermal power plants and home heating. Ward et al. (2008) reported ash content of up to 21.4% in samples of coal. By chemical analysis the obtained value was 1.73%, which is close to that observed by thermogravimetric analysis.

It is observed in Figure 3 and Figure 4 an endothermic phase related to the energy required for

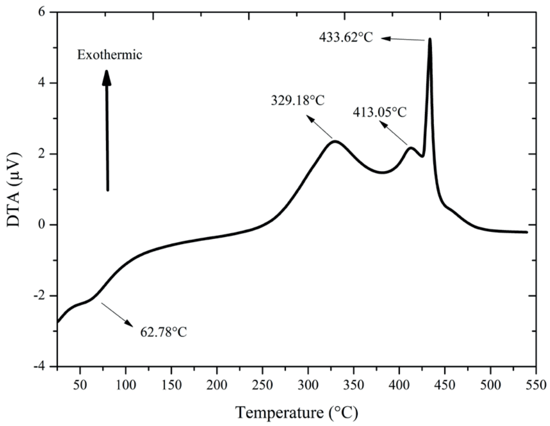

FIGURE 3 Differential thermal analysis (DTA) of combustion of fresh babassu nutshell.

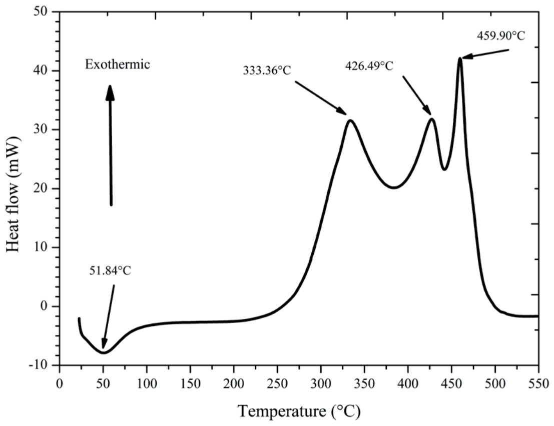

FIGURE 4 Differential scanning calorimetry (DSC) from combustion of fresh babassu nutshell.

the evaporation of the moisture in the sample, with a peak at 62.78 °C (Figure 3) and 51.84 °C (Figure 4) for the differential thermal analysis and differential scanning calorimetry, respectively. From 250°C, the reaction becomes exothermic for both analyses due to the release of energy by the combustion of organic matter. Fernandes et al. (2013) observed for banana leaves intended for energy use, exothermic reactions at 150°C for both dry and humid samples. Possibly, this was due to the lower thermal stability of this lignocellulosic waste compared to the babassu nutshell.

For the DTA curve two maximum temperature of combustion of the babassu nutshell in 329.18°C and 433.62°C and a lower peak in 413.0°C points are observed. The first peak can be attributed to the combustion of cellulose and hemicelluloses by means of the formation and emission of volatile (TSUJIYAMA; MIYAMORI, 2000). The transition from the combustion of the residual cellulose and lignin occurs, resulting in a smaller peak. After this phase intense degradation and oxidation lignin and fixed carbon occurs.

Fernandes et al. (2013) observed two exothermic events for combustion of banana leaves. The authors observed the first event between 150°C and 400°C and attributed it to the burning of the hemicelluloses and cellulose and second event between 400°C and 500°C, characteristic of the combustion of the lignin, which corroborates with this work. It is observed that the peaks that are found in the DTA curve correspond to those found in the TGA and DTG curves (Figure 2), that is, as the sample loses mass, intense energy release occurs, since the breakage occurs in biomolecules and the chemical oxidation of the main fuel elements (C and H).

Similar to that found in the DTA curve shape, we observed three well-defined exothermic peaks for the DSC curve at 333.36°C, 426.49°C and 459.90°C related to the combustion of babassu nutshell (Figure 4). Certainly, the first two peaks are mainly related to the energy released by the decomposition of cellulose and hemicelluloses in volatiles and the third peak to the energy released by the decomposition of the fixed carbon and residual lignin.

For the combustion of the *Pinus densiflora* wood, Tsujiyama and Miyamori (2000) observed in the DSC curve two main peaks at 340°C and 475°C and a minor peak at 450°C, which is similar to our findings. It is noteworthy that the differences found for the peak temperatures in the DTA and DSC curves can be attributed to the different techniques used, but the trends found are similar.

Charcoal from babassu nutshell

It is observed, in Figure 5, that in the initial stage of combustion of the fuel (drying) there is a tendency of increase mass loss for charcoals produced at higher temperatures (650°C, 750°C and 850°C) compared to the charcoals obtained at lower temperatures (450°C and 550°C). This was assumed to be due to increased hygroscopicity, consequently, the moisture of charcoal increased with the increasing of final carbonization temperature, corroborating the results of Vilas Boas et al. (2010).

After the drying phase there is an increase in the thermal stability of the charcoal with increasing final temperature of carbonization, thereby resulting in a shift of the maximum peak of weight loss for the regions of high temperature (Figure 6). In addition, there are increases in ignition temperature and burnout temperature of the fuel (Figures 7 and 8) and a decrease of the characteristic combustion index and ignition index (Table 1).

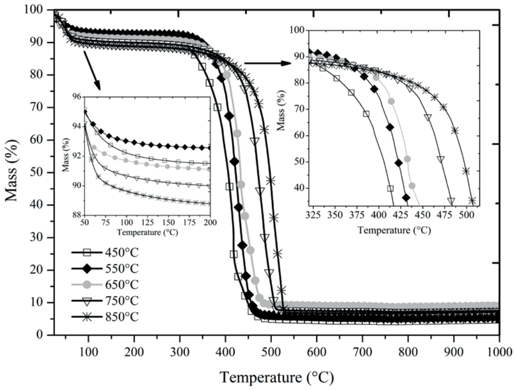

FIGURE 5 TGA curves of combustion of charcoal from babassu nut residues produced at different final temperatures of carbonization.

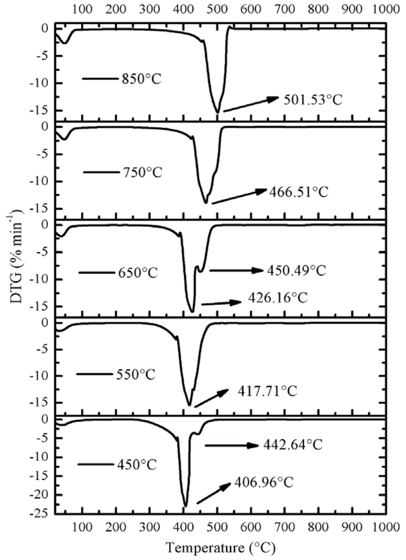

FIGURE 6 DTG curves of combustion of charcoal from babassu nut residues produced at different final temperatures of carbonization.

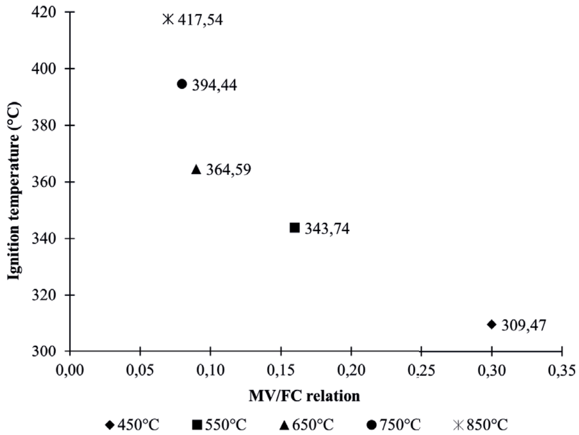

FIGURE 7 Relationship between the ignition temperature and the volatile/fixed carbon of charcoal produced at different carbonization temperatures.

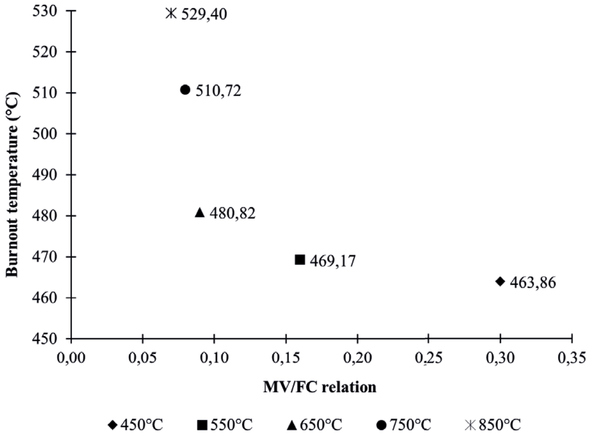

FIGURE 8 Ratio of burnout temperature and the relative volatile/fixed carbon charcoal produced at different carbonization temperatures.

The characteristic combustion index (S) reflects the reactivity of the combustion of the charcoal throughout the oxidation reaction and the higher this ratio the better the performance of the fuel during of the combustion (QIAN et al., 2012; XIONG et al., 2014). Therefore, the charcoal with the highest ignition index is easier to ignite (QIAN et al., 2012).

Xiong et al. (2014) also observed an increase in the ignition temperature and the burnout temperature and a decrease in the combustion characteristic rate with increasing final temperature of carbonization for sawn bamboo, corroborating the findings of this study.

In addition, the average rate of combustion of the charcoals produced with higher temperatures (650°C, 750°C and 850°C) was lower than the for charcoals produced at 450°C and 550 °C. The higher average rate of combustion of the charcoal produced at 850°C, in relation to the charcoals obtained at the temperatures of 650°C and 750°C, can be explained by the lower ash content of the charcoal produced at high temperature (PROTÁSIO et al., 2014b).

This result can be explained by the chemical constitution of charcoals, especially the ratios of volatile materials (VM)/fixed carbon (FC). It is known that there is a tendency to reduce the content of volatile materials and to increase the fixed carbon content and therefore decrease the VM/FC ratio with the increase of the final carbonization temperature (TITILADUNAYO et al., 2012; PROTÁSIO et al., 2014a).

The greatest amount and the rapid emission of volatile materials are factors that contribute decisively to accelerate the ignition of the fuel at a lower temperature (MOON et al., 2013). Therefore, the decrease of the VM/FC with increasing final temperature of carbonization explains the rise in time of ignition and rate corresponding to the highest combustion time and the decrease in S and D_i indexes (Table 1).

TABLE 1 Characteristic parameters of combustion of charcoal from babassu nutshell

Temp[1] (°C)	VM/FC[2]	$(dm/dt)_{max}$[3] (%·min^{-1})	$(dm/dt)_{average}$[4] (%·min^{-1})	tp[5] (min)	tig[6] (min)	S x 10^7 %^{2}/(min^2 °C^3)[7]	D$_i$x 10^3 (% min^{-3})[8]
450	0.30	22.9423	0.9548	38.5	30.0	4.93	19.86
550	0.16	15.5070	0.9541	39.3	33.1	2.67	11.94
650	0.09	15.9396	0.9129	40.5	35.7	2.28	11.04
750	0.08	13.8978	0.9281	44.5	38.7	1.62	8.08
850	0.07	15.3760	0.9337	48.1	40.8	1.56	7.82

[1] Temp: final temperature of carbonization; [2] VM/FC: volatile materials/fixed carbon ratio; [3] (dm/dt) max: maximum rate of combustion; [4] (dm/dt) average: average rate of combustion; [5] tp: corresponding to the highest rate of combustion time; [6] tig: ignition time; [7] S: characteristic combustion index; [8] Di: ignition index.

These results indicate that the increase of carbonization temperature causes a decrease of the reactivity and consequently the charcoals produced at lower temperatures are easier to ignite and exhibit better performance concerning ignition (QIAN et al., 2012). The decrease in the rate of combustion characteristic (s) and the ignition index (D$_i$) indicates that the charcoals produced at lower temperatures show better combustibility and are more easily burned (QIAN et al., 2012). Furthermore, it is observed that the charcoal produced at the final temperature of 450°C showed the highest maximum rate of combustion (22.9423% min^{-1}), due to the higher VM/FC ratio. When the charcoal is heated volatiles are emitted and mixed with oxygen in the air, promoting homogeneous combustion and increasing mass consumption.

Qian et al. (2012) evaluated samples of pyrolyzed coal at the final temperature of 450 °C, 550 °C and 650 °C and found combustion characteristic indexes of 1.24 x 10^{-7}, 1.23 x 10^{-7} and 9.40 x 10^{-8} %^{2} /(min^2 °C^3). These values are considerably lower than those observed for the charcoal of babassu nut residue at the same final temperatures of pyrolysis. These comparisons show the great potential of using babassu nut for energetic purposes, especially for the direct generation of heat in residential or industrial systems.

For the rate of ignition, Xiang-guo et al. (2006) reported the value of 8.1 x 10^3 min^{-3}% for coal, being lower than that observed for babassu nutshell charcoal produced at temperatures of 450°C, 550°C and 650°C. This indicates greater ease of ignition of charcoal of babassu obtained in these final carbonization temperatures.

In Figure 9 can be see the differential thermal analysis of combustion of the charcoal babassu nutshell produced with different final carbonization temperatures. It is observed that from 222.56°C, 251.95°C, 283.02°C, 277.23°C and 298.70 C, the reaction becomes exothermic for charcoal produced at temperatures 450°C, 550°C, 650°C, 750°C and 850°C, respectively.

In general, there is a trend of increasing temperature at which the exothermic reactions are initiated depending on the final temperature of carbonization. As discussed previously for the TGA curves (Figure 5), this occurred due to increased moisture content of charcoals produced with higher increasing final temperature of carbonization.

By the DTA curves it is noted that there was only one exothermic peak and one main combustion stage for the charcoal (Figure 9). In addition, there was an increase in the peak of energy liberation as a function of the increase of the carbonization temperature. These peaks, in turn, correspond to the DTG curves (Figure 6). For charcoals produced in the final temperatures of 450°C and 650°C there was a slight exothermic peak at 446.30°C and 450.49°C, respectively. This result can be attributed to co-combustion of the volatile materials and solid carbon.

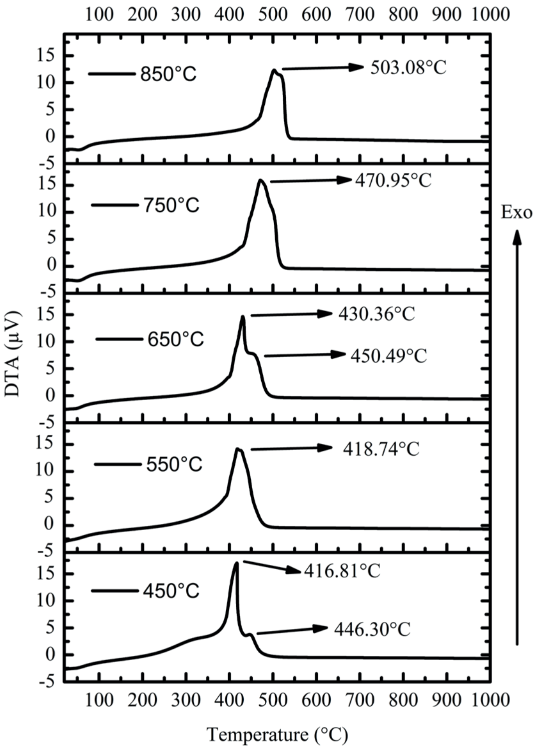

FIGURE 9 Differential thermal combustion analysis (DTA) of babassu nutshell charcoal produced at different final temperatures of carbonization.

CONCLUSIONS

The combustion of the babassu nutshell occurred in three distinct phases, and we observed that this lignocellulosic material shows aptitude for direct heat production, due to its low ignition temperature, high S and D_i indexes and low ignition time.

After the drying phase, there is an increase in the thermal stability of the charcoal with increase of the final temperature of carbonization.

The increase of the final carbonization temperature increased the ignition temperature, the burnout temperature, the ignition time and the maximum rate of combustion time.

The average rate of combustion of the charcoals produced at higher temperatures (650°C, 750°C and 850°C) was lower than that of the charcoals produced at 450°C and 550°C.

The charcoals produced at higher temperatures present greater difficulty in combustion.

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