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Characterization of *Khaya ivorensis* (A. Chev) biomass, charcoal and briquettes

Caracterização da biomassa, carvão vegetal e briquetes de *Khaya ivorensis* (A. Chev)

Mariana Dianese Alves de Moraes[1], Macksuel Fernandes da Silva[1], Pedro Vilela Gondim Barbosa[1], Rogerio Marques[1], Raissa Tavares Silva[1] and Carlos Roberto Sette Junior[1]*

Resumo

O objetivo deste estudo foi caracterizar a biomassa, o carvão vegetal e briquetes da madeira de *Khaya ivorensis* (Mogno africano) de plantação com 7 anos de idade. Cinco árvores de Mogno africano foram selecionadas e discos de madeira cortados em diferentes posições longitudinais no tronco (0, DAP, 25, 50, 75 e 100% da altura comercial). Parte dos discos foram triturados e moídos para a formação de uma amostra composta com todas as posições longitudinais, a fim de: (i) caracterizar a biomassa (densidade básica e energética, análise imediata e poder calorífico supeior); e (ii) produzir e caracterizar os briquetes (densidade aparente e energética, expansão volumétrica e resistência mecânica). Os discos cortados na altura do DAP foram utilizados para a produção de carvão vegetal para posterior caracterização (densidade relativa aparente e energética, análise imediata, poder calorífico supeior e rendimento gravimétrico). As características da biomassa e do carvão vegetal de *K. ivorensis*, indicaram parâmetros de qualidade inferiores aos de outras espécies florestais, com a mesma idade, usadas para fins energéticos. A carbonização da biomassa reduziu a densidade e o teor de materiais voláteis e aumentou os teores de carbono fixo e cinzas, o poder calorífico supeior e a densidade energética. A compactação da biomassa melhorou suas características energéticas e físico-mecânicas e é a forma tecnicamente viável para o uso energético da madeira de *K. ivorensis*, de 7 anos de idade.

Palavras-chave: Mogno africano, bioenergia, madeira juvenil.

Abstract

The objective of this study was to characterize the biomass, charcoal and briquettes of *Khaya ivorensis* (African mahogany) wood from a 7-year-old plantation. Five African mahogany trees were selected and wood discs were cut at different longitudinal positions (0, DBH, 25, 50, 75 and 100% of the commercial height). The wood discs were crushed and milled to compose a sample of all longitudinal positions in order to: (i) characterize the biomass, basic and energy densities, proximate analysis and high heating value); and (ii) produce and characterize the briquettes (apparent and energy densities, durability, volumetric expansion and tensile strength by diametric compression). The discs cut at the DBH height were used to produce charcoal for later characterization (apparent relative and energy densities, proximate analysis, high heating value and gravimetric yield). The biomass and charcoal characteristics of 7-year-old *Khaya ivorensis* indicated lower quality parameters than the main forest species used for energy purposes. Biomass compaction improved its energetic and physical-mechanical characteristics and is the indicated technique for the energetic use of 7-year-old *K. ivorensis* wood.

Keywords: African mahogany, bioenergy, juvenile wood.

INTRODUCTION

Biomass is one of the main bioenergy sources and can be obtained from harvests (branches, stumps, leaves and roots), wood processing (sawdust, shavings and bark) and from silviculture treatments (thinning and pruning). This material can be derived from energetic forests intended only for supplying raw material for energy, and from commercial forests that produce wood for other destinations (CARON et al., 2015; SPANHOL et al., 2015).

1. Escola de Agronomia, Universidade Federal de Goiás – UFG. Goiania / GO, Brasil. * Corresponding author: crsettejr@hotmail.com

Exotic species planted in commercial forests in Brazil are an important source of forest biomass. African mahogany stands out among exotic species planted in commercial forests in Brazil because it is considered a hardwood with high economic value, and is a species with rapid growth, easy adaptation and high quality for the use of solid wood (RIBEIRO; FERAZ FILHO; SCOLFORO et al., 2017). According to the Brazilian Association of African Mahogany Planters (ABPMA, 2017), there are currently 10 thousand hectares of area planted with species of the *Khaya* genus in Brazil, with most aged between one and seven years. Scientific studies in several Brazilian regions indicate different growth and biomass production rates of *Kaya* spp.; in Minas Gerais, Ribeiro, Ferraz Filho e Scolforo (2017) observed mean height values of 3 m.year^{-1} and mean DBH of 4 cm.year^{-1} at 5 years. The uses and applications of African mahogany wood in Brazil are expected to occur with 15-20-year-old trees, with thinning along the rotation when planted in denser spacing. The wood obtained from young trees derived from the thinning of plantations has different and lower characteristics, dimensions and market values when compared to mature wood with more advanced ages. In this way, knowing the characteristics and quality of African mahogany juvenile wood is essential to determine its correct application, aiming to add value to the wood. This information may support programs for genetically improving the species; contribute to adjusting technological processes and products, and finally to developing the uses of the *Khaya* genus in Brazil (SILVA et al., 2016).

The most studied possibilities for using juvenile wood are in producing wood panels (CUNHA et al., 2014; SILVA et al., 2016) and for biomass energy generation by directly using the wood or the waste generated during log cutting (DIAS JUNIOR et al., 2016; SILVA et al., 2015; SPANHOL et al. 2015). Therefore, some alternatives for using juvenile wood such as biomass densification in the form of pellets and briquettes, as well as the production of charcoal have been implemented (ARRANZ et al., 2015; NILSSON et al., 2011; TOSCANO et al., 2013).

The potential of African mahogany juvenile wood for energy purposes will depend on the energy and physical-mechanical characterization of biomass and the densified (briquette) and carbonized (charcoal) materials (QUIRINO et al., 2012; SETTE JUNIOR et al., 2016), and is an alternative for using the wood from thinning or the residue generated by log cutting.

In this context, the objective of this study was to characterize the biomass, charcoal and briquettes of juvenile wood from a 7-year-old *Khaya ivorensis* plantation.

MATERIAL AND METHODS

Characterization of the study site

Biomass, charcoal and briquette evaluations were carried out using samples obtained from 7-year-old *K. ivorensis* trees planted in 3x3 meter spacing. The forest plantation is located in the municipality of Nerópolis, a central region in the state of Goiás (16°18′28.85″S and 49°13′3.80″W), with red latosol soil, an altitude of 852 meters and an Aw climate according to the Köppen classification. The average annual precipitation is 1,432 mm, and the mean temperature is 20.4°C in the cooler months and 24.4°C in the warmer months.

Sample selection, cutting and preparation

Five *K. ivorensis* trees belonging to the medium diameter class of the plantation were randomly selected. These trees were felled and wood discs were sectioned in six positions along the trunk: 0, DBH (height of 1.3m), 25, 50, 75 and 100% of the commercial height of the tree (minimum diameter of 6 cm). The wood discs were crushed and ground to compose a composite sample with all longitudinal positions for each tree in order to: (i) characterize the biomass; and (ii) produce and characterize the briquettes.

The wood discs were cut from the five trees at the DBH (1.3 meters) and were used to determine the wood basic density and then after and to afterwards produce and characterize the charcoal, which were likewise segmented into wedges previously oven dried at 103°C and carbonized in a muffle furnace (wood carbonized at 0% moisture). The muffle furnace has dimensions of 60 x 60 x 70 cm and is equipped with a temperature and time control system, has a heating rate of approximately 1.67°Cmin^{-1} and a final temperature of 450°C, stabilizing at the final temperature for 30 minutes (ARANTES et al., 2013; ASSIS et al., 2012; SOARES et al., 2015), thus totaling 5 hours of carbonization. The samples remained cooling in the muffle furnace for approximately 12 hours after carbonization.

The apparent relative density and the charcoal yield were determined after the carbonization, considering the raw material as a reference for calculation (Gravimetric yield) and then the charcoal was crushed and ground.

Biomass and charcoal characterization

The ground biomass and charcoal were subjected to mechanical separation in an orbital shaker with sieves and intermittent beats, using 100, 60, 40 and 20 mesh sieves to characterize the granule profile of the material. The material fractions retained in each sieve were weighed to determine granule percentage.

The ground biomass and charcoal retained in the 60 mesh screen was used for proximate analysis based on ASTM E872-82 (ASTM, 2013a) and ASTM D1102-84.34 (ASTM, 2013b). These analyses allowed to determine the biomass and charcoal contents of volatile materials, ash and fixed carbon [1-(Volatile materials + ash)].

The high heating value (HHV) of the charcoal and biomass were determined according to ASTM D5865-13 (ASTM, 2013c) using a calorimetric pump at the Biomass and Bioenergy Laboratory of the Federal University of São Carlos, Sorocaba Campus /SP. The energy density of the biomass and charcoal were calculated by multiplying the HHV with basic and apparent relative densities, respectively.

Production and evaluation of briquettes

The biomass moisture content was adjusted to 12% of the samples for later briquetting in a laboratory briquetter at a temperature of 120°C, pressure of 140 $Kgf.cm^{-2}$, 5-minute compression time and 10-minute cooling time in order to compress the biomass (sample composed of wood discs collected from different longitudinal positions). The moisture content of 12% was chosen because it is within the range considered ideal for manufacturing briquettes. The briquetting conditions were experimentally defined from preliminary tests of pressing time and cooling, where the conditions chosen were those in which the briquettes presented the best shapes. The pressure and temperature exerted is within the range used in several studies (QUIRINO et al., 2012).

A total of 40g of biomass was used for each briquette, with briquettes of approximately 4 cm in length and 3 cm in diameter being produced, with 10 briquettes per tree (a total of 50 briquettes); 5 briquettes were used to determine the apparent density, volumetric expansion and durability, and the other 5 briquettes were used to determine tensile strength by diameter compression.

The moisture content of the briquettes was determined by the ratio between the mass after briquetting and after oven drying at 103°C until constant weight. The bulk density was determined by the gravimetric method and the volumetric expansion was calculated by measuring the height and diameter using a digital caliper and the volume at two different times: (i) immediately after briquetting; and (ii) 72 hours after briquetting - the time interval required for dimensional stabilization. The briquettes were packed in plastic bags so that there was no interference and/or change in humidity due to external environmental factors.

Tensile strength by diameter compression was carried out in a universal testing machine EMIC - DL30000 with a 500 kgf load cell at a constant speed of $0.3 mm.min^{-1}$ (PROTÁSIO et al., 2011; QUIRINO et al., 2012), where a charge is transversely applied to the samples. This test was defined as an adaptation of the NBR 7222/1994 (ABNT, 1994) to determine tensile strength by diameter compression in cylindrical concrete and mortar specimens.

The useful heating value of briquettes was determined according to the proposal by Sartori et al. (2001), using the average moisture content of briquettes at 12%. The briquettes were weighed to obtain the initial mass and taken to an orbital sieve shaker, where they remained for 10 minutes at 80 rotations per minute. After this procedure, the briquettes were again weighed and the final mass was obtained to calculate the durability of the briquettes.

The energy density of the briquettes was calculated by multiplying the useful calorific value of compacted biomass and the bulk density compacted biomass and the apparent density.

Statistical Analysis

The outliers, data distribution and heterogeneity of variance were measured in the statistical analysis. Descriptive statistics were performed, and the mean, minimum, maximum, median and coefficient of variation of the characteristics were determined. An analysis of variance (ANOVA) was applied to immediate analysis, high calorific value, basic and apparent relativity and energy densities to verify the material effect (biomass and charcoal) at a 5% probability level.

RESULTS AND DISCUSSION

Energy and physical characterization of biomass

The proximate analysis indicated average content of volatile materials, ashes and fixed carbon of 87.81, 1.05 and 11.17%, respectively, with coefficients of variation between 1.56 and 25.15% (Table 1).

Table 1. Energy and physical characteristics of *K. ivorensis* biomass
Tabela 1: Características energéticas e físicas de biomassa de K. ivorensis

Parameters	VC (%)	ASC (%)	TFC (%)	BD ($g.cm^{-3}$)	HHV ($Kcal.kg^{-1}$)	ED ($Gcal.m^{-3}$)
Mean	87.81	1.05	11.17	0,37	4371.89	1.12
Maximum	89.87	1.49	13.35	0,40	4410.96	1.29
Minimum	85.80	0.60	8.94	0,35	4294.80	0.95
Median	88.26	1.00	10.75	0,38	4389.96	1.09
CV (%)	1.56	25.15	12.45	5,51	0.96	10.32

VC=Volatile content; ASC=Ash content; TFC=Fixed carbon content; BD = wood basic density; HHV= high heating value; ED=Energy density; CV=Coefficient of variation.

Several scientific papers report data for volatile materials, ash and fixed carbon contents for the biomass of forest species (OLIVEIRA et al., 2010; CARNEIRO, 2013; LIU et al.,2014), with mean values of 75 to 85%, 0.2 to 2.4% and 13 to 25%, respectively. Some authors have studied the wood quality of the *Khaya* genus at more advanced ages (FRANÇA et al., 2015), however without determining the biomass energy characteristics. Souza (2015) evaluated a mixture of *K. ivorensis* and *K. senegalensis* sawdust and found an average ash content of 1.0%, supporting the value obtained in this study.

The volatile and fixed carbon content observed in this study were slightly higher and lower, respectively, than those reported in the literature for the biomass of other forest species. This difference may be associated to factors such as the age of the trees (presence of juvenile and adult wood) and the chemical composition of *K. ivorensis*. Thus, determining the lignin, holocellulose and extractive content is recommended to better explain the behavior of the species from an energetic perspective.

Fuels with high fixed carbon content exhibit slower burning, resulting in longer residence time in the burning appliances compared with other fuels which have lower fixed carbon content (OLIVEIRA et al., 2010). In addition, the content of volatile materials is related to the burning procedure in the carbonization process, where the burning is faster the higher the volatile content. Therefore, the results obtained in this study for these two parameters indicate a slight energy disadvantage for *K. ivorensis* compared to other forest biomasses.

On the other hand, the ash content obtained was low and can be considered an advantage for the species (as in all timber species), since the ash content is a relevant parameter in the boiler design and in the cleaning operation, given that biomass combustion with high ash content will require a more regular and efficient removal process due to its abrasiveness, which can cause corrosion in the metal elements of the furnaces (CARNEIRO, 2013; LIU et al., 2014).

The average basic density recorded for *K. ivorensis* was 0.37 $g.cm^{-3}$, with a coefficient of variation of 5,51% (Table 1). Scientific studies indicate mean wood basic density values for *K. ivorensis* varying from 0.36 to 0.49 $g.cm^{-3}$ in 2 to 19-year-old trees, respectively (FRANÇA et al., 2015). The difference in the mean wood basic density values indicated in the literature is associated with juvenile and adult wood and the trees' age.

The average HHV value for *K. ivorensis* biomass was 4371.89 $Kcal.kg^{-1}$ (Table 1), lower than what was recorded by Quirino et al. (2005) for 258 forest species (mean of 4732 $Kcal.kg\text{-}^{1}$) and Souza (2015) for a mixture of older *K. ivorensis* and *K. senegalensis* sawdust (4590.5 $Kcal.kg\text{-}^{1}$). The higher calorific value is defined as the amount of energy released as heat by the combustion of one mass unit of the biomass, and is considered an important parameter in determining the energy capacity of the biomass (QUIRINO et al., 2005).

The HHV value of the *K. ivorensis* biomass was low in regards to the values recorded in other studies. Regardless of the species, the calorific value varies with regards to the chemical characteristics of the wood (CARNEIRO, 2013), which in turn are influenced by the age of the tree (SETTE JUNIOR et al., 2014), among other factors. Therefore, as previously mentioned, evaluating the lignin, holocellulose and extractive contents in the wood of the species is essential to better explain the energy characteristics observed in this study.

Energy density is an important parameter for solid fuels, as it evaluates the amount of energy stored per volume of material. In this context, the average energy density of biomass recorded for *K. ivorensis* was 1.12 Gcal.m^{-3} (Table 1), higher than the value disclosed by Sette Júnior. et al. (2016) for *E. urograndis* clones (1.23 Gcal.m^{-3}) and by Protásio et al. (2011) for Eucalyptus sawdust (0.99 Gcal.m^{-3}), both calculated by using the same methods. The small differences observed are related to the basic density, calorific value and age differences between the African mahogany and Eucalyptus trees.

Energy and physical characterization of charcoal

The average characteristics of *K. ivorensis* charcoal are shown in Table 2. Scientific studies evaluating *K. ivorensis* charcoal are non-existent, which hinders a discussion of the results.

Table 2. Energy and physical characteristics of charcoal of *K. ivorensis*
Tabela 2: Energia e características físicas do carvão de K. ivorensis

Parameters	VC (%)	ASC (%)	TFC (%)	ARD (g.cm^{-3})	HHV (Kcal.kg^{-1})	ED (Gcal.m^{-3})	GY (%)
Mean	29.55	2.36	68.08	0.30	7137.77	2.13	27.34
Maximum	32.69	3.77	70.60	0.33	7308.48	2.43	28.27
Minimum	27.02	1.49	64.82	0.28	6829.44	1.92	26.78
Median	29.28	2.26	68.91	0.30	7198.80	2.05	27.20
CV (%)	7.02	23.05	3.08	6.83	2.81	8.12	1.90

VMC=Volatile content; ASC=Ash content; TFC=Fixed carbon content; ARD=apparent relative density; HHV= high heating value; ED=Energy density; GY=Gravimetric yield; CV=Coefficient of variation.

The average volatile material contents in charcoal produced from *K. ivorensis* wood wood was 29.55% (27.02 to 32.69%), with a CV of 7.02%, higher than what has been reported by other authors. For example, Oliveira et al. (2010) recorded a volatile material content of 14.6% in *Eucalyptus pellita* charcoal, while Protásio et al. (2014) found 18.5% for charcoal from *Eucalyptus* sp, clones with the same carbonization conditions.

High volatile material content (28%) was observed for the charcoal produced from *Pinus* sp. wood (CONTI et al., 2016), but with a maximum temperature of 500°C; different from the temperature used in this study. Charcoals with high volatile material content are not indicated for use in the steel industry, reducing the quality of the pig iron produced.

The average ash content in the *K. ivorensis* charcoal found in this study was 2.36% (Table 2), with minimum 1.49% and maximum values of 3.77%. Protásio et al. (2014) obtained 2.2% ash content for Eucalyptus charcoal under the same carbonization conditions. With slightly different conditions, Conti et al. (2016) obtained 3.4% ash content for *Pinus* sp. charcoal.

Charcoal ash content is directly linked to the ratio of mineral materials in the wood of origin (QUIRINO et al. 2012). In addition, the presence of ash compromises the charcoal quality, mainly for its use in the steel industry since it wears out the blast furnace and can compromise the iron quality, with consequent formation of cracks (CARNEIRO, 2013).

The fixed carbon content of charcoal ranged from 64.82 to 70.60% in the five studied *K. ivorensis* trees (Table 2). This variation in values is lower than that found by other authors for different forest species under the same carbonization conditions (OLIVEIRA et al., 2010; PROTÁSIO et al., 2014). Fuels with high fixed carbon content burn slower than those that have lower fixed carbon content. They are suitable for thermo-reduction of iron ore during the production of pig iron and steel in the steel industry (OLIVEIRA et al., 2010).

The average apparent relative density value of *K. ivorensis* charcoal was 0.30 g.cm^{-3} (Table 2). This parameter is one of the most important properties for iron production in the steel industry, since

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the denser the charcoal for the same fixed carbon content, the longer the residence time of the metal load in the thermal reserve zone of the blast furnace, and also the higher the equipment capacity. This gives the charcoal higher mechanical strength and higher heat capacity per unit volume, since high productivities in the steel industries are obtained using high-density raw materials (CARNEIRO, 2013).

The evaluation of proximate analysis and apparent relative density indicated that the *K. ivorensis* charcoal produced with 7-year-old wood is not recommended as an iron ore thermo-conductor in the steel industry.

The HHV of *K. ivorensis* charcoal was on average 7137.77 Kcal.kg^{-1} $^{-1}$ (6829.44 to 7308.48 Kcal.kg-^{1}) with a coefficient of variation of 2.8% (Table 2), being considered within the range of values commonly mentioned in the literature (e.g. SOARES et al. 2015, who reported 7.000 Kcal.kg^{-1}). The HHV is the main parameter used to express the capacity of generating energy to replace other fuels, for example oil derivatives (SOARES et al., 2015; SANTOS et al., 2016).

The average energy density found in this study for the *K. ivorensis* charcoal was 2.13 Gcal.m^{-3} (Table 2), lower than the recorded by Protásio et al. (2014) and Santos et al. (2016) for the charcoal produced from Eucalyptus species and clones (3.05 and 2.40 Gcal.m^{-3}, respectively). This difference is related to the variables of density and calorific value of the charcoals.

The carbonization yield from *K. ivorensis* charcoal was 27.34% (ranging from 26.78 to 28.27% among the five studied trees) (Table 2), and was lower than what was recorded by other authors for the charcoal of other species under the same carbonization conditions (ASSIS et al., 2012). In addition to the heating rate and final carbonization temperature, gravimetric yield and other energy characteristics are also influenced by the chemical composition of the biomass, as indicated in the literature (dos Santos et al., 2016). Therefore, determining lignin and holocellulose content is recommended to better explain the behavior of the *K. ivorensis* species, as previously mentioned.

Biomass x Charcoal

Carbonization promotes the carbon concentration in the charcoal structure as a function of the decrease in mass due to the output of condensable and non-condensable gases, where a series of physical and chemical processes modify the energetic and physical-mechanical characteristics of the biomass (CARNEIRO, 2013). It is important to evaluate and relate the characteristics of the material before and after the carbonization in order to determine the magnitude of changes in biomass characteristics after carbonization. Therefore, Figure 1 and Table 3 present a comparison between the energy and physical characteristics of the *K. ivorensis* biomass and charcoal, indicating statistical differences ($p < 0.05$) for all characteristics.

The volatile material content was significantly higher in the biomass (87.8%) than in the charcoal (29.5%), as expected. The reduced volatile material in the charcoal is related to its elimination during pyrolysis due to the increase in temperature (CARNEIRO, 2013).

On the other hand, the average *K. ivorensis* biomass was 11.2% for fixed carbon content, being statistically lower than what was recorded for charcoal (67.8%). The increase in total fixed carbon

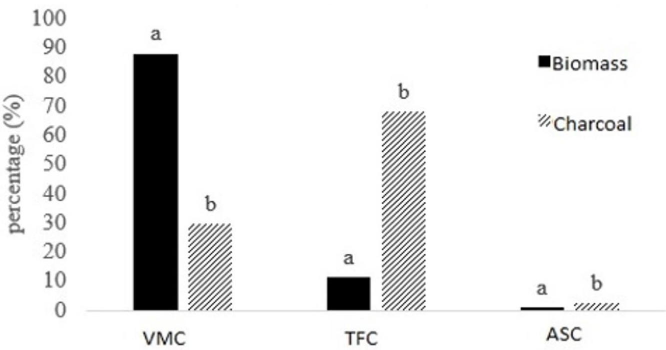

Figure 1. Volatile matter content (VMC), fixed carbon (TFC) and ashes (ASC) of the biomass and charcoal of *K. ivorensis*. Means followed by the same letter, for each variable do not differ among each other at a 5% significance level by the Test F.

Figura 1: Teor de materiais voláteis (VMC), carbon fixo (TFC) e cinzas (ASC) da biomassa e carvão vegetal de *k. ivorensis.* As médias seguidas da mesma letra, para cada variável, não diferem entre si em um nível de significância de 5% pelo Teste F.

Table 3. Densities and high heating value of the biomass and charcoal of *K. ivorensis.*
Tabela 3: Densidade e poder calorífico superior da biomassa e do carvão vegetal de *K. ivorensis*.

Material	Density ($g.cm^{-3}$)	high heating value ($Kcal.kg^{-1}$)	Energy density ($Gcal.m^{-3}$)
Biomass	0.38 a	4371.89 a	1.64 a
Charcoal	0.30 b	7137.77 b	2.13 b

Means followed by the same letter, for each variable, do not differ from each other at 5% of significance by Test F.

in the charcoal when compared to the biomass is due to the extensive loss of volatile materials with increased temperature, at the same time as it raises the concentration of materials which are more resistant to the heat action (fixed carbon) in the solid product (SANTOS et al., 2016). Therefore, fixed carbon content is one of the most important energetic indicators to measure charcoal quality, because the higher the fixed carbon contents of the charcoal, the greater the volumetric use in steel furnaces (ARANTES et al., 2013).

The average ash content in the *K. ivorensis* biomass was statistically lower than the charcoal (Figure 1). The ash content represents the material that was not burned, and is a relevant parameter in designing and cleaning the furnace, as previously mentioned. Note that the combustion of biomass with high ash content will require a more regular and efficient removal process due to its abrasiveness, which in the long term can corrode the metal elements of the burners (CARNEIRO, 2013; LIU et al., 2014) and affect the charcoal quality (CARNEIRO, 2013).

The basic wood density exhibited a significant reduction to the order of 25% after carbonization (0.38 to 0.30 $g.cm^{-3}$) (Table 3). This reduction is related to an increase in the material porosity caused by the thermo-degradation of the chemical constituents that make up the cell wall – the density gives the charcoal greater mechanical resistance and higher heat capacity per unit volume, since high productivities in the steel industry are a consequence of raw materials that have high density values (CARNEIRO, 2013).

The increase in the average high calorific value in the charcoal than in the biomass (4371.89 to 7137.77 $Kcal.kg^{-1}$) was 61%. The high heating value is of great importance, mainly for charcoal usage as an energy source in replacing petroleum derived fuels, and its increase compared to the biomass is related to the carbonization temperature, as the charcoal presents higher fixed carbon content with an increase in the calorific value at the carbonization temperature of 450-500 °C (CARNEIRO, 2013).

The average energy density for the *K. ivorensis* biomass (1.64 $Gcal.m^{-3}$) is statistically lower than what was observed in charcoal (2.13 $Gcal.m^{-3}$) (Table 3). This increase in energy density is related to the increase in the the higher heating resulting from the carbonization, in spite of the reduced density in the charcoals. Another way to increase the biomass energy density besides carbonization is to increase the energy concentration per unit volume through its densification, for example (SETTE JUNIOR et al., 2016).

Energy and physical-mechanical properties of briquettes

The average apparent density of *K. ivorensis* briquettes was 1.22 $g.cm^{-3}$ (Table 4), a value similar to what was presented by Souza (2015) for briquettes of a mixture of *K. ivorensis* and *K. senegalensis* sawdust (1.2 $g.cm^{-3}$) produced with a temperature of 120 °C, a pressure of 100 $Kgf.cm^{-2}$ and a compaction and cooling time of five to seven minutes. Silva et al. (2015) found lower values of mean bulk density for *Eucalyptus* sp. sawdust briquettes (0.9 $g.cm^{-3}$) and of *Pinus* sp. (1.0 $g.cm^{-3}$) sawdust produced at 1250 $kgf.cm^{-2}$ with a compaction time of 30 seconds.

The apparent density of the *K. ivorensis* briquettes (1.22 $g.cm^{-3}$) was about three times greater than basic wood density (0.38 $g.cm^{-3}$, Table 1) and apparent relative density of charcoal (0.30 $g.cm^{-3}$, Table 2). This fact confirms that the pressure applied during the compacting process affects the briquette density, where the applied pressure and the final density are linearly related (SILVA et al., 2015). The mean useful heating value was 3775.26 $kcal.kg^{-1}$, about 600 $kcal.kg^{-1}$ lower than the high heating value (Table 1). This reduction is associated with the moisture content of the briquettes (12%), as the presence of water in the biomass decreases the calorific value (CARNEIRO, 2013).

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Table 4. Characteristics of *K. ivorensis* briquettes
Tabela 4: Características dos briquetes de *K. ivorensis*

Parameters	BD ($g.cm^{-3}$)	UHV ($kcal.kg^{-1}$)	ED ($Gcal.m^{-3}$)	EXP (%)	DUR (%)	TSDC (MPa)
Mean	1.22	3775.26	4.61	1.49	99.62	6.56
Maximum	1.25	3809.53	4.76	2.44	100.00	8.29
Minimum	1.14	3711.12	4.34	0.78	97.95	4.83
Median	1.23	3791.16	4.60	1.43	99.75	6.12
CV (%)	2.05	0.96	1.98	24.03	0.43	16.94

BD=Apparent density; UHV: useful heating value; ED=Energy density; EXP=Volumetric expansion; DUR=Durability; TSDC=Tensile strength by diametral compression; CV=Coefficient of variation.

The average energy density of the briquettes was 4.61 $Gcal.m^{-3}$ higher than what was recorded for wood (1.12 $Gcal.m^{-3}$) and charcoal (2.13 $Gcal.m^{-3}$) (Tables 1 and 2). The data obtained prove that the biomass densification through briquetting raises the energetic density, as also observed in other scientific studies (e.g. SETTE JUNIOR et al., 2016; TENORIO et al., 2016). In this context, the high bulk density in the briquettes promotes greater energy density; the energy is concentrated in a smaller unit of space, highlighting the economic and energetic advantages of the biomass compaction process (PROTÁSIO et al., 2011).

The low energy density of the biomass compared to petroleum and mineral coal implies high costs of transport and storage. In this sense, the research and development of techniques aiming at a higher concentration of energy per unit volume (such as in briquetting) are fundamental for increasing the use of biomass as an energy source. The compaction and the increase in the energy density add value to the final product (the briquettes), increase handling and storage capacity, reduce humidity, provide thermal regularity and effective combustion during the combustion process (PAULA et al., 2011).

The mean volumetric expansion value of *K. ivorensis* briquettes was 1.49%, with a coefficient of variation of 24.03%. Protásio et al. (2011) studied the compaction of vegetal biomass to produce solid biofuels, and found an average volumetric expansion value of 15.6% for briquettes produced with *Eucalyptus* sp. sawdust 72 hours after manufacture, but without applying temperature. The briquettes tend to expand longitudinally after the briquetting process. This expansion varies depending on the type of biomass and storage conditions, especially the moisture content of these conditions (SILVA et al., 2015).

The tensile strength by diametral compression (TSDC) of *K. ivorensis* briquettes was 6.56 MPa, higher than the value recorded by Silva et al. (2015) for *Eucalyptus* sp. sawdust briquettes (mean of 1.2 Mpa) and for *Pinus* sp. sawdust briquettes (mean of 0.7 Mpa), both without applying temperature. The TSDC is one of the most important properties in evaluating the briquettes' quality, since it indicates the stacking capacity and the impact caused by the abrasion during transport, since the briquettes suffer friction and may crumble (SOARES et al., 2015).

The durability test complements the TSDC (SILVA et al., 2015) and analyzes the briquette's resistance when subjected to falling, impacts and abrasions. The mean durability values of 99.62% observed in this study indicates that *K. ivorensis* briquettes are considered to be poorly friable, meaning that they have good durability and low mass loss when handled.

The "in natura" biomass usually presents inefficiencies for energetic use, especially for its high moisture content, low density and calorific value, causing high transport and handling costs. However, as noted in the results obtained for *K. ivorensis* briquettes, these problems can be reduced if this biomass is densified, providing more energy per unit volume, and complementarily improving handling and transportation (FELFLI et al., 2011; LIU et al., 2014).

Although the results indicate the technical feasibility of using African mahogany biomass in the form of briquettes, it is important to determine the financial and economic viability of briquette production from the thinning wood or the residue from its dewatering in sawmills. It is worth mentioning that African mahogany species have noble wood and great economic potential for internal and external commercialization, and can be used in the furniture, civil construction, panel and laminate industries, among others (PINHEIRO et al., 2011). The energetic characterization of African mahogany wood, charcoal and briquettes presented in this study aim at the best usage for the thinning wood (when performed), the residues generated during cutting/sawing in sawmills, or for trunk parts not used for the described purposes such as upper parts of the trees.

CONCLUSION

The biomass and charcoal characteristics of 7-year-old *Khaya ivorensis* indicated lower quality parameters than the main forest species used for energy purposes.

Biomass compaction improved its energetic and physical-mechanical characteristics and is the indicated technique for the energetic use of 7-year-old *K. ivorensis* wood.

REFERENCES

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 7222**: Argamassa e concreto: determinação da resistência à tração por compressão diametral de corpos-de-prova cilíndricos. Rio de Janeiro, 1994.

ABPMA - ASSOCIAÇÃO BRASILEIRA DOS PRODUTORES DE MOGNO AFRICANO. 2016. Disponível em:< http://abpma.org.br/ >. Acesso em: 14 jan. 2017.

ASTM – AERICAN SOCIETY FOR TESTING AND MATERIALS. **ASTM E872-82**: Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels. Phyladelphia, 2013a.

ASTM – AERICAN SOCIETY FOR TESTING AND MATERIALS. **ASTM D1102-84.34**: Standard Test Method for Ash in Wood. West conshohocken, 2013b.

ASTM – AERICAN SOCIETY FOR TESTING AND MATERIALS. **ASTM D5865-13**: Standard Test Method for Gross Calorific Value of Coal and Coke, West Conshohocken, 2013c.

ARANTES, M. D. C.; TRUGILHO, P. F.; DA SILVA, J. R. M., ANDRADE, C. R. 2013. Características do carvão de um clone de *Eucalyptus grandis* w. Hill ex maiden x *Eucalyptus urophylla* S. t. Blake. **Cerne**, Lavras, v. 19, n. 3, p. 423-431, 2013.

ARRANZ, J. I.; MIRANDA, M. T.; MONTERO, I.; SEPÚLVEDA, F. J.; ROJAS, C. V. Characterization and combustion behaviour of comercial and experimental wood pellets in South West Europe. **Fuel**, Londres, v. 142, p. 199–207, 2015.

ASSIS, M. R.; POTRÁSIO, T. P.; ASSIS, C. O.; TRUGILHO, P. F.; SANTANA, W. M. S. Qualidade e rendimento do carvão vegetal de um clone híbrido de Eucalyptus grandis x *Eucalyptus urophylla*. **Pesquisa Florestal Brasileira**, Colombo, v. 32, n. 71, p. 291-302, 2012.

CARNEIRO, A. C. O. Pirólise lenta da madeira para produção de carvão vegetal. In: SANTOS, F.; COLODETTE, J.; QUEIROZ, J. H. (Ed.) **Bioenergia e Biorrefinaria**: Cana-de-açúcar e Espécies Florestais. Viçosa: Os Editores, 2013. p. 429-455.

CARON, B. O.; ELOY, E.; SOUZA, V. Q.; SHMIDT, D.; BALBINOT, R.; BEHLING, A.; MONTEIRO, G. C. Quantificação da biomassa florestal em plantios de curta rotação com diferentes espaçamentos. **Comunicata Scientiae**, Bom Jesus, v. 6, n. 1, p. 106-112, 2015.

CONTI, R.; FABBRI, D.; VASSURA, I.; FERRONI, L. Comparison of chemical and physical indices of thermal stability of biocharges from differet biomass by analytical pyrolysis and thermal gravimetry. **Journal of Analytical and Applied Pyrolysis**, Oxford, v. 122, p. 160-168, 2016.

CUNHA, A. B.; LONGO, B. L.; RODRIGUES, A. A.; BREHMER, D. R. Produção de painéis de madeira aglomerada de *Eucalyptus benthamii, Eucalyptus dunnii,*e *Eucalyptus grandis*. **Scientia Forestalis**, Piracicaba, v. 42, n. 102, p. 259-267, 2014.

FELFLI, F. F.; MESA, J. M.; ROCHA, J. D.; FILIPPETTO, D.; LUENGO, C. A.; PIPPO, W. A. Biomass briquetting and its perspectives in Brazil. **Biomass and Bioenergy,** Oxford, v. 35, n. 1, p. 236 – 242, 2011.

FRANÇA, T. S. F. A.; ARANTES, M. D. C.; PAES, J. B.; VIDAURRE, G. P.; OLIVEIRA, J. T. S.; BARAÚNA, E. E. P. Características anatômicas e propriedades físico-mecânicas das madeiras de duas espécies de mogno africano. **Cerne**, v. 21, n. 4, p. 633-640, 2015.

LIU, Z. J.; FEI, B. H.; JIANG, Z. H.; CAI, Z. Y.; LIU, X. E. Important properties of bamboo pellets to be used as commercial solid fuel in China. **Wood ScienceTechnology**, n. 48, p. 903–917, 2014.

NILSSON, D.; BERNESSON, S.; HANSSON, P. Pellet Production from agricultural raw materials – A systems study. **Biomass bioenergy**, v. 35, p. 679-689, 2011.

OLIVEIRA, A. C.; CARNEIRO, A. C. O.; VITAL, B. R.; ALMEIDA, W.; PEREIRA, B. L. C., CARDOSO, M. T. Parâmetros de qualidade da madeira e do carvão vegetal de *Eucalyptus* pellita F. Muell. **Scientia Florestalis**, Piracicaba, v. 38, p. 431-439, 2010.

PAULA, L. E. R.; TRUGILHO, P. F.; REZENDE, R. N.; ASSIS, C. O.; BALIZA, A. E. R. Produção e avaliação de briquetes de resíduos lignocelulósicos. **Pesquisa Florestal Brasileira**, Colombo, v. 31, n. 66, p. 103-112, 2011.

PROTÁSIO, T. P.; GOULART, S. L.; NEVES, T. A.; TRUGILHO, P. F.; RAMALHO, F. M. G.; QUEIROZ, L. M. R. S. B. Qualidade da madeira e do carvão vegetal oriundos de floresta plantada em Minas Gerais. **Pesquisa Florestal Brasileira**, Colombo, v. 34, n. 78, p. 111- 123, 2014.

PROTÁSIO, T. P.; ALVES, I. C. N.; TRUGILHO, P. F.; SILVA, V. O.; BALIZA, A. E. R. Compactação de biomassa vegetal visando a produção de biocombustíveis sólidos. **Pesquisa Florestal Brasileira**, Colombo, v. 31, n. 68, p. 273-283, 2011.

QUIRINO, W. F.; PINHA, I. V. O.; MOREIRA, A. C. O. M.; SOUZA, F.; TOMAZELLO FILHO, M. Densitometria de raios x na análise da qualidade de briquetes de resíduos de madeira. **Scientia Forestalis**, Piracicaba, v. 40, n. 96, p. 525-536, 2012.

QUIRINO, W. F.; VALE, A. T.; ANDRADE; A. P. A.; ABREU, V. L. S.; AZEVEDO, A. C. S. Poder calorífico da madeira e de materiais lignocelulósicos. **Revista da Madeira**, v. 89, p. 100-106, 2005.

RIBEIRO, A.; FERAZ FILHO, A. C.; SCOLFORO, J. R. S. O Cultivo do Mogno Africano (*Khaya* spp.) e o Crescimento da Atividade no Brasil. **Floresta e Ambiente**, v. 24, p. 2-11, 2017.

SANTOS, D. R. S.; SETTE JUNIOR, C. R.; SILVA, M. F.; YAMAJI, F. M.; ALMEIDA, R. A. Potencial de espécies de bambu como fonte energética. **Scientia Forestalis**, Piracicaba, v. 44, n. 111, 2016.

SARTORI M. M. P.; FLORENTINO, H. O.; BASTA, C.; LEÃO, A. L. Determination of the optimal quantity of crop residues for energy in sugarcane crop management using linear programming in variety selection and planting strategy. **Energy**, v.26, p.1031-1040, 2001.

SETTE JÚNIOR, C. R.; FREITAS, P. C.; FREITAS, V. P.; YAMAJI, F. M., ALMEIDA, R. A. Production and characterization of bamboo pellets. **Revista Bioscience Journal**, v. 32, p. 922-930, 2016.

SETTE JÚNIOR, C. R; TOMAZELLO FILHO, M; SILVA JÚNIOR, F. G; LACLAU J. P. Alterações nas características químicas da madeira com a substituição do K por Na em plantações de Eucalipto. **Revista Árvore**, v. 38, n. 3, p. 569-578, 2014.

SILVA, J. G. M.; VIDAURRE, G. B.; ARANTES, M. D. C.; BATISTA, D. C.; SORANSO, D. R., BILLO, D. F. Qualidade da madeira de mogno africano para produção de serrados. **Scientia Forestalis**, Piracicaba, v. 44, p. 181-190, 2016.

SILVA, D. A.; CHRISTO, E. R.; BELHING, A.; MAYER, S. L. S.; PELANDA, K. A.; SIMETTI, R. Potencial e qualidade da madeira de desbaste de teca para produção de biocombustível. **Pesquisa Florestal Brasileira**, Colombo, v. 35, n. 83, p. 299-305, 2015.

SOARES, V. C.; BIANCHI, M. L.; TRUGILHO, P. F.; HöFLER, J.; PEREIRA, A.J. Análise das propriedades da madeira e do carvão vegetal de híbridos de eucalipto em três idades. **Cerne**, v. 21, p. 191-197, 2015.

SOUZA, C. O. **Resíduos de mogno africano e eucalipto para briquetagem**. 2015. 58 p. Monografia (Graduação em Engenharia Florestal), Universidade Federal do Espírito Santo, Jerônimo Monteiro, 2015.

SPANHOL, A.; NONES, D. L.; KUMABE, F. J. B.; BRAND, M. A. Qualidade dos *pellets* de biomassa florestal produzidos em Santa Catarina para a geração de energia. **Revista Floresta**, Curitiba, v. 45, p. 833-844, 2015.

TENORIO, C.; MOYA, R.; TOMAZELLO FILHO, M.; VALERT, J. Quality of pellets made from agricultural and forestry crops in Costa Rican tropical climates. **Bioresources**, v. 10, n. 1, p. 482-498, 2016.

TOSCANO, G.; RIVA, G.; PEDRETTI, E. F.; CORINALDESI, F.; MENGARELLI, C.; DUCA, D. Investigation on wood pellet quality and relationship between ash content and the most important chemical elements.**Biomass and Bioenergy**, v. 56, p. 317-322, 2013.

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