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Characterization of biomass, charcoal and briquette of *Phyllostachys aurea* Carr. ex A. & C. Rivière

Caracterização da biomassa, do carvão vegetal e de briquete de *Phyllostachys aurea* Carr. ex A. & C. Rivière

Carlos Roberto Sette Júnior[1], Pedro Augusto Fonseca Lima[2], Domingos Manuel Mendes Lopes[3], Pedro Vilela Gondim Barbosa[4], Ademilson Coneglian[5] e Rogério de Araújo Almeida[6]

Resumo

O objetivo do trabalho foi avaliar as características energéticas e físico-mecânicas da biomassa, do carvão vegetal e de briquetes de *Phyllostachys aurea*, visando determinar seu potencial para o uso energético. Foram coletados colmos maduros em área experimental, com 5 anos de idade, para a caracterização da biomassa (densidade básica e energética, análise imediata e poder calorífico superior), produção e caracterização dos briquetes (densidade aparente e energética, resistência mecânica e da durabilidade) e de carvão vegetal (densidade relativa aparente e energética, análise imediata, poder calorífico superior e rendimento gravimétrico). A biomassa, carvão vegetal e briquetes de *P. aurea* apresentaram características energéticas e físico-mecânicas que indicam o seu potencial para o uso energético. A carbonização da biomassa promoveu a redução da densidade de materiais voláteis e o aumento do carbono fixo, das cinzas, do poder calorífico superior e da densidade energética.

Palavras-chave: bambu; bioenergia; características energéticas;

Abstract

The objective of this study was to evaluate the energy and physical-mechanical characteristics of biomass, charcoal and briquettes of *Phyllostachys aurea*, to determine its potential for energy purposes. Mature culms were selected and collected in a 5-year old experimental area to (i) characterize the biomass (basic and energy densities, proximate analysis and high heating value), (ii) production and characterize the briquette (bulk and energy densities, mechanical resistances and durability) and (iii) charcoal (apparent relative and energy densities, proximate analysis, high heating value and gravimetric yield). The biomass, charcoal and briquettes from *P. aurea* exhibited energy and physical-mechanical characteristics that indicate their potential for energy applications. The carbonization of the biomass of reduced the density and volatile material contents and increased fixed carbon, ash contents, calorific value and energy density.

Keywords: bamboo; bioenergy; physical-mechanical properties.

INTRODUCTION

The use of renewable energies in Brazil showed progress in 2016, due mainly by the thermal generation reduction based on petroleum derivatives and by the increased generation from biomass (BRASIL, 2017). Therefore, research related to the application of agricultural and forestry biomass for the generation of energy was increased (SANTOS et al., 2016; SETTE JÚNIOR et al., 2016), and can be used in several ways: as firewood or chips for direct burning, or as charcoal and briquettes.

[1]PhD Professor at Forest Science Department. UFG – Universidade Federal de Goiás. P.O. Box 131 – 74690-900 – Goiânia, GO, Brasil: E-mail: crsettejr@hotmail.com.

[2]PhD Student. UFG – Universidade Federal de Goiás. P.O. Box 131 – 74690-900 – Goiânia, GO, Brasil: E-mail: pedrofons@gmail.com.

[3]PhD Professor at Forest Science and Landscape Architecture Department. UTAD – Universidade de Trás-os-Montes e Altodouro. P.O. Box 5000-801 – Vila Real, Portugal. E-mail: dlopes@utad.pt.

[4]Master's Degree student. UFG – Universidade Federal de Goiás. P.O. Box 131 – 74690-900 – Goiânia, GO, Brasil. E-mail: pvgbflorestal@hotmail.com.

[5]PhD Professor at Forest Science Department. UEG - Universidade Estadual de Goiás. GO 330 Km 241 - 75780000 - Ipameri, GO, Brasil. E-mail: coneglian@ueg.br.

[6]PhD Professor at Rural Engineering Department. UFGO – Universidade Federal de Goiás. P.O. Box 131 – 74690-900 – Goiânia, GO, Brasil: E-mail: rogerioufg@gmail.com.

Brazil currently counts on 7.8 million hectares of planted trees, with *Eucalyptus* being the main species used for the consumption of wood for industrial purposes. *Eucalyptus* production in the year 2016 was 21.2 million m³, of which 14% was used as charcoal, mainly by the steel industries (IBÁ, 2017).

Densified materials, such as pellets and briquettes, are among the most widely used biomass forms of energy use in the World (ARRANZ et al., 2015; TOSCANO et al., 2013). This material shows characteristics superior to other biomass products, such as firewood and charcoal, especially when comparing mass and energy densities (ARRANZ et al., 2015). Higher density reduces transport costs and is efficient for energy conversion (CARONE et al., 2011).

Although wood and agricultural crops, such as sugar cane, are the main biomass energy sources currently used in Brazil (GARCIA, et al., 2013), other alternative biomass sources with potential for energy generation, such as agricultural/forest residues and grasses, such as bamboo species, have been used. Scientific studies have evaluated the biomass and energy production, and carried out the energetic characterization of charcoal from bamboo (BALDUINO JÚNIOR et al., 2016; BRITO et al., 1987; SANTOS et al., 2016) and of its use in a densified form (ARAGÓN-GARITA et al., 2016; DIAS JÚNIOR. et al., 2016; FREITAS et al., 2016 TENORIO et al., 2015). Despite the studies mentioned, there are still few evaluations of important bamboo species, such as *Phyllostachys aurea* Carr. ex A. & C. Rivière and new studies are essential due to the development of the growing demand for alternative and sustainable renewable energy.

P. aurea has a great power for vegetative dispersion due to its leptomorphic rhizomes and to its diverse applications, such as in the construction of fences, handicrafts, for soil erosion control and also as energy source (PASTORE et al., 2012). Small plantations of this exotic species can be found in Brazil in southern Bahia, Minas Gerais, Paraná, Rio de Janeiro and at São Paulo States (OLIVEIRA et al., 2009). Only two scientific studies evaluating its culm for energy purpose have been reported (ARAGÓN-GARITA et al., 2016; TENORIO et al., 2015), both indicating its potential for energy application. The application of bamboo for energy purposes has been increasing gradually over the years. However, the lack of technical and scientific knowledge of bamboo species, mainly information on its use, has limited the development of this bamboo for energy purposes (SANTOS et al., 2016). Thus, in order to minimize the lack of information and encourage bamboo cultivation; Law 12,484 of 2011 was created (BRASIL, 2011), establishing the National Incentive Management Policy and the Cultivation of Bamboo (Política Nacional de Incentivo ao Manejo e ao Cultivo do Bambu – PNMCB), with the objective of developing bamboo cultivation in Brazil.

The evaluation parameters of biomass and charcoal (proximate analysis, calorific value, basic, apparent relative and energy densities, gravimetric yield), as well as of briquettes (bulk and energy densities, expansion, durability and mechanical resistance) are commonly used to determine the energy potential in several scientific studies (ANDRADE et al., 2015; DIAS JÚNIOR et al., 2016; SANTOS et al., 2016; SETTE JÚNIOR. et al., 2016; THABUOT et al., 2015). These parameters are fundamental to select which biomass can be used for the various applications, either for steel production or for direct burning (BALDUINO JÚNIOR. et al., 2016).

The parameters of biomass, charcoal and briquettes have indicated, for different materials, the differences between the products, with emphasis on the increase of the carbon content and calorific value in the biomass after the pyrolysis and the mass and energy densities in the biomass after compaction into pellets or briquettes (ARRANZ et al., 2015; LIU et al., 2014a; MIRANDA et al., 2015). Thus the production of charcoal and briquettes improves the energy and physical-mechanicals characteristics of *"in natura"* biomass.

The objective of this study was to perform the energetic and physical-mechanical characterization of biomass, charcoal and briquettes of *Phyllostachys aurea*.

MATERIAL AND METHODS

Study area and sample collection

Mature culms were collected in an 5-year-old experimental area of *P. aurea*, located in the central region of the State of Goiás, Brazil (16° 36′ S and 49° 17′ W). This region is characterized by its tropical climate, classified as Aw according to the classification of Köppen and Geiger, with a mean annual temperature of 23.0°C and rainfall of 1,432 mm. Soil is classified as dark Oxisol.

P. aurea culms were selected based on the criteria determined by Hidalgo-López (2003): located in the center of the clump, with high hardness and dark color. In this way, 10 mature culms were selected and cut randomly. In addition, a segment of 50 cm in length was sectioned at the DBH height (1.3 m) of each culm for biomass, charcoal and briquette characterization.

Sample preparation and biomass characterization

Two cylindrical 5 cm length specimens were obtained from each segment of the bamboo culms in order to produce and characterize the charcoal (total of 20 samples). The other samples were used to (i) characterize the biomass and (ii) to produce the briquettes. Culms were transformed into sawdust using a Wiley mill and subjected to a mechanical separation in the orbital shaker of sieves with intermittent beats to select from the fraction retained in the international No. 24 sieve, of 60 mesh. The high heating value (HHV) was determined from the ground biomass using a calorimeter, according to ABNT NBR 8633 (ABNT, 1984); and volatile matter, ash and fixed carbon content, according to ABNT NBR 8112 (ABNT, 1986). The basic density of the culms was determined by the hydrostatic method, as described in ABNT NBR 11941 (ABNT, 2003). Energy density was calculated as the product of HHV by the basic density.

Production and characterization of the charcoal

The samples were first dried at 105 °C and carbonized in a muffle furnace. The furnace (60 cm x 60 cm x 70 cm) was equipped with a temperature and time control system, with a heating rate of 1.67 $°C.min^{-1}$ and final temperature of 450 °C, stabilizing at the final temperature during 30 min (SANTOS et al., 2016; SOARES et al., 2015). The apparent relative density and gravimetric yield was determined after carbonization. The charcoal was then milled with a Willey-type knife mill and subjected to a mechanical separation in the orbital shaker of intermittent sieves, in order to select the fraction separated in the international No. 24 sieve with 60 mesh opening. The HHV, the contents of volatile matter, ash, fixed carbon and energy density were determined using the standards and methodologies described in the biomass characterization item.

Production and characterization of briquettes

The biomass was dried at 105 °C (± 2 °C) to constant weight and the moisture content was adjusted to 12%, using a water sprayer and precision balance, as proposed by Silva et al. (2015). The moisture content of 12% was chosen because it is within the range considered ideal for briquette manufacture.

The compaction of *P. aurea* biomass in the form of briquettes was carried out in a laboratory briquette press applying 140 $kgf.cm^{-2}$; a temperature of 120 °C with a 5-minute compression time and 15 min forced-air cooling. The briquetting conditions were experimentally defined from preliminary tests of pressing time and cooling, when the briquettes presented the best formations were chosen. The pressure exerted is within the range used in several studies (PROTÁSSIO et al., 2011; QUIRINO et al., 2012). A total of 40 g of biomass was used for each briquette, obtaining at the end a briquette of approximately 4 cm in length and 3cm in diameter (15 briquettes).

The bulk density of 5 briquettes was obtained through equation 1.

$$B_d = \frac{Wi}{V} \quad (1)$$

Where:
B_d = bulk density ($g.cm^{-3}$);
W_i = Initial weight of the briquette at 12% moisture (g);
V = Volume of briquette at 12% moisture (cm^3).

The splitting test by diameter compression was performed in 5 briquettes using a universal testing machine EMIC - DL30000, with a 500 kgf load cell, at a constant speed of 0.3 $mm.min^{-1}$ (PROTÁSSIO et al., 2011; QUIRINO et al., 2012), where a load is applied on the samples in the transverse direction. The test was carried out from an adaptation of the standard ABNT - NBR 7222 (ABNT, 1994) to determine the splitting test by diameter compression in cylindrical samples of concrete and mortar.

The durability of briquettes was determined by weight loss of the samples, as described by Toscano et al. (2013) and Liu et al. (2014b), and by equation 2. Five briquettes were weighed to obtain the initial weight and submitted to a vibrating sieve for 10 minutes at 80 rotations per minute. The briquettes were again weighed and the final mass was obtained after this procedure.

$$Dur = 100 - \left[\frac{w_{id} - w_{fd}}{w_{id}} x\ 100\%\right] \quad (2)$$

Where:
Dur = Durability (%);
w_{id} = Initial weight of the briquettes (g);
w_{fd} = Final weight of the briquettes (g).

The energy density was calculated by multiplying the HHV of the biomass by the bulk density of each briquettes.

Data Analysis

The completely randomized design (CRD) was used. The outliers, data distribution and heterogeneity of variance were evaluated. The means were obtained and the standard deviation and coefficient of variation was calculated for all variables. The analysis of variance (ANOVA) was used for the results of the proximate analysis, high heating value and energy density to verify the effect of the material (biomass and charcoal) at a 5% probability level.

RESULTS AND DISCUSSION

Characterization of biomass and charcoal

The results of volatile, ash and fixed carbon contents of the biomass and choarcal of *P. aurea* are shown in Figure 1, with statistically different mean values.

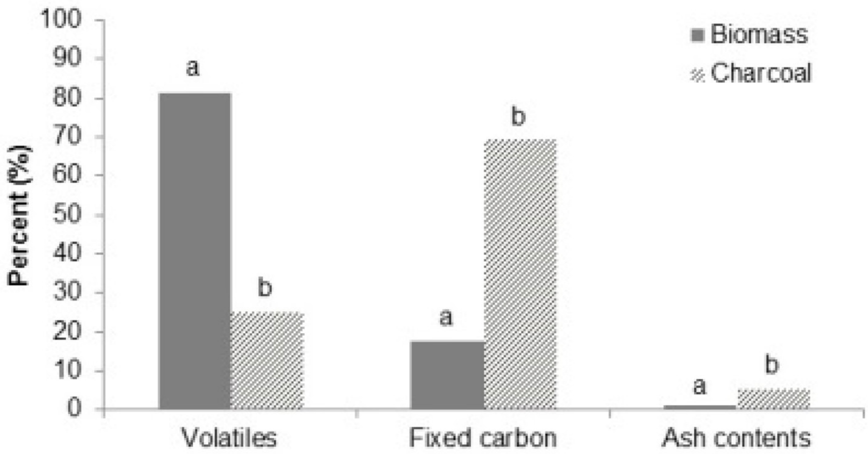

Figure 1. Contents of volatiles; ash and fixed carbon of the biomass and choarcal of *P. aurea*. Means followed by the same letter, for each variable, do not differ from each other at 5% significance by the F Test.
Figura 1. Teores de materiais voláteis, carbono fixo e cinzas da biomassa e do carvão vegetal de *P. aurea*. Médias seguidas da mesma letra, para cada variável, não diferem entre si a 5% de significância pelo Teste F.

The content of volatile materials was statistically higher in the biomass (81.5%) than in the charcoal (25.4%), being within the range commonly mentioned in the literature. Aragón-Garita et al. (2016) and Tenorio et al. (2015) evaluating different types of biomass from Costa Rica, recorded volatile material contents of 75.3 and 78.3% for *P. aurea*, respectively. Sette Júnior. et al. (2016) found volatile material contents around 78% when characterizing the biomass of several species of bamboo within the same experimental area and sampling procedures as Balduino Júnior. et al. (2016) when evaluating the energy potential of *Bambusa vulgaris* biomass, at 3years; who obtained mean values of 82.3%. The amount of volatile material is directly related to the carbonization burning process, because the higher the content of volatiles, the faster is the burning. And the reduced volatile matter contentes in charcoal are related to its elimination during pyrolysis , due to temperature increase (CARNEIRO et al., 2013).

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The mean fixed carbon content of the *P. aurea* biomass was 17.6% and is consistent with the results presented by Aragón-Garitta et al. (2016) for *P. aurea* biomass (18.5%); Santos et al. (2016) for *Bambusa tuldoides*, *Bambusa vulgaris* and *Dendrocalamus asper* (22-23%); and Balduino Júnior et al. (2016) for *B. vulgaris* (15%). High fixed carbon content in fuels provides a slower burning, with a longer residence time of the material inside the burners compared to other fuels with lower fixed carbon contents (SPANHOL et al., 2015).

The fixed carbon content of charcoal (69.4%) was statistically higher than that of biomass, being within the range reported in the literature for charcoal of bamboo species – 71.5 to 73.5% (SANTOS et al. 2016) and 62 to 67% (ANDRADE et al. 2015). The increase of fixed carbon in charcoal compared to biomass occurs due to the massive loss of volatile products with increasing temperature, while concentrating materials more resistant to the action of the heat (fixed carbon) in the solid product (SANTOS et al., 2016). This is one of the most essential energy indicators when measuring the quality of coal, because the higher the fixed carbon content of coal, the greater its potential use in steel kilns (ARANTES et al., 2013).

The ash content of the *P. aurea* biomass obtained in this study was 0.9%, lower than the ash content indicated by several studies with other bamboo species (BALDUINO JÚNIOR. et al., 2016; SANTOS et al., 2016; SETTE JÚNIOR. et al., 2016). Commonly, bamboo species shows high ash content due to high silica contents present in the chemical composition of the culms (TAMOLANG et. al., 1979). Performing chemical analyses on *P. aurea* culms is recommended in order to understand disparities in ash contents found in the literature.

The low ash content observed in the culms of *P. aurea* compared to other bamboo species in an advantage for energy applications. The ash content represents the material that was not burned and it is a relevant parameter in the design of the boiler and in its cleaning, since the combustion of biomass with high ash contents will require a more regular and efficient removal process. The abrasiveness corrosion occurs in the metallic elements of the burners in the long term (CARNEIRO et al., 2013; LIU et al., 2014a; THABUOT et al. 2015) and can affect the quality of charcoal (CARNEIRO et al., 2013).

It should be noted that the mean values of volatile materials fixed carbon and ash contents of *P. aurea* biomass observed in this study are within the range of values observed for other species used by the forestry sector, such as for *Eucalyptus* species (ARANTES et al., 2013, SANTOS et al., 2016; SOARES et al., 2015).

Basic density was statistically higher in the culms (0.48 g.cm^{-3}) compared to apparent relative density in the charcoal (0.40 g.cm^{-3}) (Table 1). The apparent relative density of charcoal obtained in this study is within the range of values indicated in the literature (e.g. SANTOS et al. 2016; 0.32 to 0.48 g.cm^{-3} for several bamboo species) and when compared with other species used for energy generation. Protássio et al. (2011) reported that *P. aurea* exhibited values similar to those for *E. urograndis*. This parameter is one of the most important properties for the production of pig iron in the steel industry, since 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 the greater the load capacity of the equipment. This characteristic provides the charcoal with greater mechanical strength and higher heat capacity per unit volume, because high productivities in the steel industry are due to high-density raw materials (CARNEIRO et al., 2013).

Table 1. Basic and apparent relativite density, high heating value, energy density and gravimetric yield of the biomass and charcoal of *P. aurea*.
Tabela 1. Densidade básica e relativa aparente, poder calorífico superior, densidade energética e rendimento gravimétrico da biomassa e do carvão vegetal de *P. aurea*.

Material	Basic density (g.cm^{-3})	Highest calorific value (kcal.kg^{-1})	Energy density (Gcal.m^{-3})	Gravimetric yield (%)
Biomass	0.48 a (0.03)	4403.52 a (155.2)	2.11a (0.12)	-
Charcoal	0.40 b (0.02)	6775.08 b (176.8)	2.72 b (0.21)	32.70 (1.50)

Means followed by the same letter, in the column, do not differ from each other at 5% significance by Test F. Standard deviation between parentheses.
Médias seguidas da mesma letra, na coluna, não diferem entre si a 5% de significância pelo Teste F. Desvio padrão entre parênteses.

The high heating value (HVV) of *P. aurea* biomass was 4,403.5 kcal.kg^{-1}; statistically lower than that of charcoal (6775.1 kcal.kg^{-1}; Table 1). The use of bamboo culms for energy is considered very important, with calorific values of the biomass varying between 4,500-5,400 kcal.kg^{-1} (UEDA, 1981). Soares et al. (2015) reported 7,000 kcal.kg^{-1} for charcoal; corroborating the results obtained in this study. The high heating value is the main parameter to express energy generation capacity in substitution to other fuels, for example, petroleum derivatives (SANTOS et al., 2016; SOARES et al., 2015). Other scientific papers also show this variation from HHV of biomass and charcoal of bamboo species (ARANTES et al., 2013; BALDUINO JÚNIOR. et al., 2016; LIU et al., 2014b).

Energy density is an important parameter for solid fuels because it represents the amount of energy per volume of material. In this study, the energy densities of biomass and charcoal were 2.11 and 2.72 Gcal.m^{-3} respectively (Table1), with significant difference. The highest value of energy density observed in charcoal is related to the HHV, increases due to pyrolysis, despite the reduction in charcoal density. Santos et al. (2016) evaluated the energy density of three bamboo species and found values from 1.96 to 2.80 Gcal.m^{-3} for biomass and 2.16 to 3.20 Gcal.m^{-3} for charcoal.

The energy density of the bamboo biomass can be considered low when compared to other sources, for example, of petroleum and coal (COUTO et al., 2004). One of the ways to increase the energy density of biomass is to increase the concentration of energy per volume, for example, through biomass densification (SETTE JÚNIOR. et al., 2016).

The charcoal gravimetric yield of *P. aurea* was 32.7%, at a final temperature of 450 °C and at a heating rate of 1.67 °C.min^{-1}. The results of other scientific studies, with the same carbonization conditions, indicate values ranged from 30 to 37% for several bamboo species (BRITO et al., 1987; BALDUINO JÚNIOR. et al., 2016; SANTOS et al., 2016). Generally a high gravimetric yield in charcoal is desirable, due to the greater use of the wood in the carbonization furnaces and, consequently, greater energy production (NEVES et al., 2011).

Physical and mechanical characterization of briquettes

The bulk and energy densities, mechanical resistances and durability of *P. aurea* briquettes are shown in Table2.

Table 2. Bulk and energy mechanical resistances and durability of *P. aurea* briquettes.
Tabela 2. Densidade aparente e energética, resistência mecânica e durabilidade dos briquetes *P. aurea*.

Briquette (n°)	Bulk density (g.cm^{-3})	Energy density (Gcal.m^{-3})	Mechanical resistance (MPa)	Durability (%)
1	1.16	5.13	1.91	99.49
2	1.17	5.18	2.15	99.99
3	1.16	5.15	1.98	99.99
4	1.16	5.11	1.94	99.99
5	1.15	5.09	2.30	99.99
Mean	1.16	5.13	2.07	99.89
CV (%)	0.66	0.80	8.8	0.22

The mean bulk density of *P. aurea* briquettes was 1.16 g.cm^{-3}. Tenorio et al. (2015) evaluated *P. aurea* pellets and found a bulk density of 1.17 g/cm^{-3}. Freitas et al. (2016) evaluated briquettes of *B. vulgaris*, *D. asper* and *B. tuldoides* and recorded a bulk density of 1.22 g.cm^{-3}.

The mean energy density of *P. aurea* briquettes (Table 2) was 5.13 Gcal.m$^{-3;}$ being 59 and 47% higher than the energy density of biomass and charcoal respectively (Table 1). The data show that densification of biomass by briquetting increases the energy density, as also observed in other research (FREITAS et al., 2016; SETTE JÚNIOR. et al., 2016; TENORIO et al., 2015). In this context, the high apparent density of briquettes promotes a high energy density, with more energy concentrated in a smaller unit of space, highlighting the economic and energetic advantages of the biomass compaction process (PROTÁSSIO et al., 2011).

Freitas et al. (2016) evaluated three bamboo species (*B. vulgaris, D. asper* and *B. tuldoides*) and found values of energy density ranging from 5.14 to 5.50 Gcal.m^{-3}. Quirino et al. (2012) recorded similar values when evaluating briquettes of *Eucalyptus* residues, in the same experimental conditions as of this study (4.87 to 5.78 Gcal.m^{-3}).

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P. aurea briquettes exhibited an average tensile strength by diametral compression (mechanical resistance) of 2.07 MPa (Table 2). Mechanical resistances values reported in the literature for bamboo briquettes and other agroforestry materials range from 0.20 to 4.4 MPa (FREITAS et al., 2016; QUIRINO et al., 2012; SILVA et al., 2015), depending on the conditions of briquetting process conditions (pressure and temperature) and to the biomass characteristics.

This parameter is one of the most important properties in evaluating the briquettes quality, since it indicates the stacking capacity, the impact caused by the transport, the abrasion (briquettes suffer friction and can crumble) and water absorption (SOARES et al., 2015).

The durability test complements the tensile strength by diametral compression (SILVA et al., 2015) and evaluates the mechanical strength of the briquette when subjected to falls, impacts and abrasions. The mean durability values of 99.9% observed in this study (Table 2) indicate that *P. aurea* briquettes are considered to be little friable, i.e., they have good durability and low mass loss when handled. Liu et al. (2014b) evaluated the properties of *Phyllostachys edulis* in pellets production and found durability values ranging from 95 to 98%, showing the importance of durability in dense materials, mainly in the handling and transportation of the material.

CONCLUSIONS

(A) ***Phyllostachys aurea*** biomass and charcoal characteristics:
- The mean contents of volatile materials, fixed carbon and ash, for biomass and charcoal, were 81.5-25.4%; 17.6-69.4% and 0.9-5.2%;
- The basic apparent relative and energy densities was 0.48 $g.cm^{-3}$; 2.11 $Gcal.m^{-3}$ for biomass and 0.40 $g.cm^{-3}$; 2.72 $Gcal.m^{-3}$ for charcoal;
- The high heating value was 4,403.5 $kcal.kg^{-1}$ in the biomass and 6,775.1 $kcal.kg^{-1}$ in the charcoal.

(B) Characteristics of *Phyllostachys aurea* briquettes:
- The briquettes had a bulk density of 1.16 $g.cm^{-3}$ and energy density of 5.13$Gcal.m^{-3}$;
- The mean tensile strength of the briquettes was 2.07 MPa, with a durability of 99.9%.

(C) *Phyllostachys aurea* biomass, charcoal and briquettes presented energetic and physical-mechanical characteristics that indicate their potential for energy application.
(D) The carbonization of *Phyllostachys aurea* biomass reduced density and volatile materials and increased fixed carbon, ash, calorific value and energy density.

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REFERENCES

ANDRADE, J. K. B.; OLIVEIRA, E.; LIMA, C. R.; CALEGARI, L. COSTA JÚNIOR, D.S. Potencial produtivo de carvão vegetal da espécie *Bambusa vulgaris* Schrad. cultivado em Timon, MA. **Revista Verde de Agroecologia e Desenvolvimento Sustentável**, Pombal, v. 10, n. 3, p. 29-33, 2015.

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

ARAGÓN-GARITA, S.;MOYA, R.;BOND, B.;VALAERT, J;TOMAZELLO-FILHO, M. Production and quality analysis of pellets manufactured from five potential energy crops in the Northern Region of Costa Rica. **Biomass and Bioenergy**, Oxford, v. 87, s/n., p. 84-95, 2016.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 11941/ 2003:** Determinação da densidade básica. São Paulo, 2003.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 7222/94**: Argamassa e concreto: determinação da resistência à tração por compressão diametral de corpos de prova cilíndricos. São Paulo, 1994.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 8112/86**: Carvão vegetal: Análise Imediata. São Paulo, 1986.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 8633/84**: Carvão vegetal - Determinação do poder calorífico. São Paulo, 1984.

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, s/n., p. 199–207, 2015.

BALDUINO JÚNIOR., A. L.; BALDUINO, T. Y.; FRIEDERICHS, G.; CUNHA, A. B.; BRAND, M. A. Energetic potential of bamboo culms for industrial and domestic use in Southern Brazil. **Revista Ciência Rural**, Santa Maria, v. 46, n. 11, p. 1963-1968, 2016.

BRASIL. **Lei n° 12.484 de 2011** - Política Nacional de Incentivo ao Manejo Sustentado e ao Cultivo do Bambu, 2011. Disponível em: < http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2011/lei/l12484.htm >. Acesso em: 10 nov. 2016

BRASIL. MINISTÉRIO DE MINAS E ENERGIA. **BEN - Balanço Energético Nacional.** Relatório Síntese: ano base 2015. Brasília: MMA, 2017.

BRITO, J. O.; TOMAZELLO FILHO, M.; SALGADO, A. L B. Produção e caracterização do carvão vegetal de espécies e variedades de bambu. **Revista IPEF**, Piracicaba, v. 36, s/n., p. 13-17, 1987.

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: UFV, 2013. p. 429-455.

CARONE, M. T.; PANTALEI, A.; PELLERANO A. Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of Olea europaea. **Biomass and Bioenergy**, Oxford, v. 35, s/n., p. 402–10, 2011.

COUTO, L.; MÜLLER, M. D.; SILVA JÚNIOR, A. G.; CONDE, L. J. N. Produção de pellets de madeira - o caso da Bio-energy no Espírito Santo. **Biomassa & Energia**. Viçosa, v. 1, n. 1, p.45-52, 2004.

DIAS JÚNIOR, A. F.; ANDRADE, A. M.; CARVALHO A. M.; BENÍCIO E. L.; BRITO J. O. Produção de briquetes de moinha de carvão vegetal e resíduos lignocelulósicos visando uso bioenergético. **Revista Scientia Forestalis**. Piracicaba, v. 44, n.110, p. 453-462, 2016.

FREITAS, P. C.; SILVA, M. F.; SILVA, R. T.; CONEGLIAN, A.; SETTE Jr, C. R. Evaluation of briquetes from bamboo species produced under different temperatures. **International Journal of Current Research**, v. 8, n. 9, p. 39260-39265, 2016.

GARCIA, D. P.; CARASCHI, J. C.; VENTORIM, G. Caracterização energética de pellets de madeira. **Revista da Madeira**, Curitiba, v. 135, s/n., p. 14-18, 2013.

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

HIDALGO-LÓPEZ, O. **Bamboo**: The gift of the gods. Colombia: D'Vinni Ltda, 2003. p. 142-153

IBÁ - INDÚSTRIA BRASILEIRA DE ARVORE. **Relatório Anual IBÁ**. Brasília: IBÁ, 2015.80 p.

LIU, Z.; QUEK, A.; BALASUBRAMANIAN, R. Preparation and characterization of fuel pellets from woody biomass, agro-residues and their corresponding hydrochars. **Applied Energy**, n. 113, p.1315–1322. 2014a.

LIU, Z. J.; FEI, B. H.; JIANG, Z. H.; CAI, Z. Y. LIU, X. E. Important properties of bamboliuo pellets to be used as commercial solid fuel in China. **Wood Science Technology**, Nova Iorque, v. 48, s/n., p. 903–917. 2014b.

MIRANDA, T; MONTEIRO, I.; SEPÚLVEDA, F. J.; ARRANZ, J. I.; ROJAS, C.V.; NOGALES, S. A Review of Pellets from Different Sources. **Materials,** Basel, v. 8, p. 1413-1427, 2015.

OLIVEIRA, F. H. **Utilização de bambu na construção de quadros de bicicletas. Monografia em Engenharia de Materiais.** 2009. 60 p. Monografia (Graduação em Engenharia de Materiais). Universidade Federal do Rio Grande do Sul, Porto Alegre, 2009.

NEVES, T. A.; PROTÁSIO, T. P.; COUTO, A. M.; TRUGILHO, P. F.; SILVA, V. O.; VIEIRA, C. M. M. Avaliação de clones de *Eucalyptus* em diferentes locais visando à produção de carvão vegetal. **Pesquisa Florestal Brasileira**, Colombo, v. 31, n. 68, p. 319-330, 2011.PASTORE, M. RODRIGUES, R. S.; SIMÃO-BIANCHINI, R.; FIGUEIRAS, T. S. **Plantas exóticas invasoras na reserva biológica do Alto da Serra de Paranapiacaba**. São Paulo: Instituto de Botânica, 2012. 46 p.

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

TAMOLANG, F. N.; LOPEZ, F. R.; SEMANA, J. A.; CASIN, R. F.; ESPILOY, Z. B. Properties and utilization of Philippine erect bamboos. **Forpride digest,** Laguna, v. 99, n. 34, p. 31-41, 1979.

SANTOS, D. R.; SETTE JÚNIOR, C. R.; SILVA, M. F.; YAMAJI, F. M.; ALMEIDA, R. A. Potencial de espécies de Bambu como fonte energética. **Revista Scientia Forestalis**, Piracicaba, v. 44, n. 111, p. 751-758, 2016.

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**, Uberlândia, v. 32, n. 4, p. 922-930, 2016.

SILVA, D. A.; YAMAJI, F. M.; BARROS, H. L.; RÓZ, A. L.; NAKASHIMA, G. T. Caracterização de biomassas para a briquetagem. **Revista Floresta**, Curitiba, v. 45, n. 4, p. 713-722, 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. **Revista Cerne**, Lavras, v. 21, n. 2, p. 191-197, 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, n. 4, p. 833-844, 2015.

TENORIO, C.; MOYA, R.; TOMAZELLO FILHO, M.; VALERT, J. Quality of pellets made from agricultural and forestry crops in Costa Rica tropical climates. **Bioresources**, Raleigh, v. 10, n. 1, p. 482-498, 2015.

THABUOT, M.; PAGKETANANG, T.; PANYACHAROEN, K.; MONGKUT, P.; WONGWICHA, P. Effect of applied pressure and binder proportion on the fuel properties of holey bio-briquettes. **Energy Procedia**, v. 79, s/n., p. 890-895, 2015

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. **Journal Biomass and Bioenergy**, Oxford, v. 56, s/n., p. 317-322, 2013.

UEDA, K. Bamboo industry in Japan, present and future. In: IUFRO WORLD CONGRESS, 17., Kyoto, 1981. **Proceedings...** Kyoto: Wood Research Institute/Kyoto University, 1981. p. 2-14.

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