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RESEARCH ARTICLE

EVALUATION OF BRIQUETTES FROM BAMBOO SPECIES PRODUCED UNDER DIFFERENT TEMPERATURES

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ABSTRACT

The present study aims to evaluate the quality of briquettes produced from the biomass of bamboo species under different briquetting temperature conditions. The species selected were *Dendrocalamus asper*, *Bambusa vulgaris*, *Bambusa tuldoides* and, for comparative purposes, a hybrid of *Eucalyptus urophylla* x *Eucalyptus grandis*, which were cut and transformed in sawdust to produce briquettes at three temperatures: room temperature ±30ºC, 80ºC, 120ºC. Biomass and briquettes characteristics were assessed. The species used for production of briquettes did not influence the highest calorific value, the bulk and energetic densities. Bamboo briquettes showed lower volumetric expansion values and higher values of tensile strength by diametral compression and durability when compared to eucalyptus, indicating their potential for energy use in the form of densified materials. The use of temperature on bamboo and eucalyptus biomass compacting improved the physical and mechanical properties of the briquettes.

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INTRODUCTION

The use of renewable energy matrices for power generation in Brazil is of prominence due to its great potential, particularly energy produced from water and biomass (Costa and Prates, 2005). Presenting itself as one of the greatest agroforestry producers in the world, Brazil can increase renewable sources share in the energy matrix (MME, 2014) as soon as it starts to better seize the large amount of biomass produced in its territory. A great interest on the use of biomass as biofuels has emerged over the last years, driven by the concern of reducing environmental impacts, carbon emissions and by a global energy consumption increase (Masia *et al.*, 2010). The use of biomass as a renewable energy source stands out with a high development potential for the years to come, as it is one of the main options for diversifying the energy matrix and reducing the dependence on fossil fuels (ANEEL, 2015). Biomass can be targeted to the production of densified material in the form of briquettes. Briquetting is one of the processes where pressure and temperature are applied on a set of disperse particles, resulting in one solid body of higher density (Silva *et al.*, 2015). The production of these materials is by the reconstruction of particulate matter, with or without the addition of binders (Liu *et al.*, 2014), comprising a means of efficient use for biomass, presenting a sustainable alternative for the use of waste with advantages for being a high energy material, due to its high density and low moisture content, its relative ease of transportation and storage, which explain this market's rapid growth, both in terms of production as well as consumption (Gonçalves *et al.*, 2013; Nguyen *et al.*, 2015). The quality of briquettes is influenced by several factors, such as the size of biomass particles, as well as the pressure, temperature and time exerted during compacting (Neves *et al.*, 2011; Quirino *et al.*, 2012). Temperature is one of the most significant factors in the briquetting process, for the use of high temperatures causes lignin – a structural polymer present in wood and lignocellulosic waste – to act as a binding agent of particles, since at 80ºC or above lignin softens, working as a particle adhesive (Nguyen *et al.*, 2015; Quirino *et al.*, 2012), which justifies the non-use of artificial binders, such as resins and waxes, reducing the product's cost. In addition, the use of high temperatures reduces biomass moisture content, positively influencing on the briquette's useful calorific value (Karunanithy *et al.*, 2012). Among the alternative biomasses are bamboos, which present an accelerated growth rate and rapid biomass production, placing them in a prominent position (Kobayashi *et al.*, 2004). Bamboo biomass energy

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shows great potential, for there are many processing manners (thermal or biochemical conversion), which can generate different energetic products, such as coal, gas and biofuels (Truong and Ahn, 2014). In this context, the Brazilian Policy to Incentive Sustainable Management and Cultivation of Bamboo (Brasil, 2011) (PNMCB, acronym in Portuguese) was established by the government, and has as its main goal, the development of bamboo cultures in Brazil, regarding it as key to the country's economic and social development. The scientific studies assessing the production and quality of briquettes at different briquetting temperature (Paula *et al*., 2011) are scarce, and no papers evaluating densified biomass in the form of briquettes of bamboo species have been reported in the literature, making it essential to develop new research projects, given the increasing demand for alternative and sustainable renewable energy. Within this context, this study aims to evaluate the quality of briquettes produced from the biomass of bamboo species under different briquetting temperature conditions.

MATERIALS AND METHODS

Selection of species, collection and sample preparation

Mature culms of the species *Bambusa vulgaris* Schard. ex J.C. Wendl, *Dendrocalamus asper* (Schult. And Schult.) Backer ex. K. Heynekand *Bambusa tuldoides* Munro, in an experimental area of 5-year old, were selected and collected in clumps in the GoiásState, Brazil (16º 36' S and 49º 17' W).The altitude in the region is 730m, and the climate is type Aw (hot and semi-humid) according to the Köppen's classification (Köpeen and Geiger, 1928), with a well-defined dry season from May to September, average annual precipitation of 1.400 mm and soil characterized as dark Oxisol. The criteria defined by Hidalgo-Lopez (2003) were considered to select mature culms: placed in the center of the thicket, with high hardness and dark color. A total of five culms were randomly chosen for each species, and 30 cm samples near the DBH (1.3 meters high) and between the nodeswere made through cutting. A total of five trees of 6-year-old *Eucalyptus grandis x Eucalyptus urophylla* hybrids (popularly known as *E. urograndis*) were selected from a forest plantation located in the same area used to sample bamboo culms, for comparison. These five trees were cut and pruned, and short logs of 30 cm in length were cut the trunk near the DBH (1.3 meters high). Samples of bamboo and eucalyptus were used for the production of briquettes, being turned into sawdust using a crusher and a Wiley knife mil and mechanically separated in the orbital shaker of sieves, with intermittent beats, in order to select a fraction retained on #24 international sieve, with a 60 mesh net. Each species' highest calorific value (HCV) was determined by means of a calorimeter, as per the Brazilian Association of Technical Standards Regulation NBR #8633 (AssociaçãoBrasileira de NormasTécnicas – ABNT, 1984).In sequence, the sawdust was dried at 105 °C (± 2 °C) until constant weight, moisture content adjusted to 8% with the aid of a water sprayer and a precision scale, as proposed by Silva *et al.* (2015). The 8% moisture content was chosen for it is considered to be ideal for the manufacturing of briquettes (Lucena *et al*., 2008)

Production of briquettes

Biomass compacting of bamboo species and the eucalyptus hybrid was made in a laboratory briquetting machine, with a pressure of 140kgf.cm^{-2}, compacting time of 5 minutes and 15 minutes for cooling under forced ventilation, with varying room temperature at (± 30ºC), 80°C e 120°C. The start of treatment at a temperature of 80°C used to heat was established according to the average basic specific mass, obtained from bamboo culms and wood disks, considering recommendations contained in Lutz (1974) and Feihl and Godin (1970). Briquetting conditions were experimentally defined through preliminary pressing and cooling time tests, choosing those briquettes which showed the best formations. The exerted pressure is within the range used in several works (Neves *et al*., 2011; Konish *et al*., 2011). For each briquette, 40g of biomass were used, obtaining at the end, a briquette of approximately 4cm length x 3cm diameter. A total of 10 briquettes were produced for each species/temperature, totaling 120 briquettes.

Mechanical and Physical Properties of Briquettes

Bulk density

The bulk density of each briquette (Bd in g.cm^{-3}) was obtained through equation 1, whereas the individual volume (V in cm³) was determined by equation 2.

$$Bd = \frac{Mi}{V} \quad (1)$$

$$V = \frac{\pi}{4d^2L} \quad (2)$$

Energy density

The energy density was obtained by multiplying the biomass highest calorific value by each briquette's bulk density.

Volumetric expansion

The volumetric expansion of briquettes was calculated by measuring the height and diameter of 10 briquettes for each species/temperature, and subsequent volume calculations in two different stages: (i) immediately after briquetting and (ii) 72 hours after briquetting – intermission time necessary for dimensional stability of briquettes.

Tensile strength by diametral compression

Tensile strength by diametral compression was performed in 5 briquettes for each species/temperature, using a Emic DL30000 universal testing machine, with a 500kgf load cell, at a constant rate of 0,3 mm.min^{-1} (Neves *et al*., 2011; Souza, 2014), where a load is transversely applied on samples. The test was executed from an adaptation of ABNT regulation NBR #7222 (1994) to determine the tensile strength by diametral compression in cylindrical samples of concrete and mortar.

Durability

The briquettes' durability (Du in %) was determined by the samples' loss of mass, as described by Toscano *et al.* (2013) and Liu *et al*. (2014), using equation 3. Five briquettes for each species/temperature were weighed to obtain their initial mass (m_i in g), taken to a vibrating screen, where they remained for 10 minutes, at 80 rotations per minute. Once this procedure was finished, the briquettes were once again weighed for final mass (m_f in g).

$$Du = 100 - \left[\frac{m_i - m_f}{m_i} x100\right] \quad (3)$$

Statistical analysis

The completely randomized design was used with seven treatments (four species and three temperatures) to obtain the statistical analysis. "Outliers" were measure by the Box-Plot method, the distribution data normality by the Shapiro-Wilk methodand the heterogeneity of variance by the Bartlett methodand Levene. The data obtained presented distribution normality and homogeneity of variance, to which a variance analysis (ANOVA) was applied, verifying the effects of treatments (species and temperature) in each property; Turkey's testing was applied, adjusted to a probability of 95%. The association of briquettes' characteristics through Person's correlations was determined.

RESULTS AND DISCUSSION

Results found for the average values of highest calorific value, bulk and energy density-of the species studied are presented in Table 1, and no significant species effect was observed. Highest calorific value, which ranged 4515-4663 kcal.kg[1] for the four species studied is the amount of energy released by biomass combustion, an important variable in order to know the energetic capacity of biomass (Santos *et al*., 2011).

Table 1. Average values for highest calorific value, bulk and energy density of bamboo and eucalyptus briquettes.Averages followed by standard deviation. HCV = highest calorific value. Averages followed by the same letter in the column do not differ by Tukey's test at 5% significance

Species	HCV(Kcal.kg^{-1})	Bulk Density (g.cm^{-3})	Energy Density (Gcal.m^{-3})
B. tuldoides	4515.1 a (38.1)	1.13 a (0.09)	5.14 a (0.21)
B. vulgaris	4662.9 a (45.2)	1.14 a (0.12)	5.35 a (0.56)
D. asper	4526.2 a (29.7)	1.20 a (0.07)	5.46 a (0.32)
E. urograndis	4657.6 a (41.2)	1.15 a (0.10)	5.39 a (0.47)

Table 2. Average values for bulk and energy density of briquettes produced under different temperatures. Averages followed by standard deviation. Averages followed by the same letter in the column do not differ by Tukey's test at 5% significance

Temperature	Bulk density(g.cm^{-3})	Energy density(Gcal.m^{-3})
± 30ºC	1.05 a (0.06)	4.85 a (0.22)
80ºC	1.20 b (0.04)	5.52 b (0.19)
120ºC	1.22 b (0.05)	5.63 b (0.28)

Varanda and Caraschi (2009), in studying the characterization of energetic properties in *Bambusa vulgaris* found the average value 4553.05 kcal.kg^{-1} for this species' biomass highest calorificvalue. Carneiro *et al*. (2014), studying the hybrid of *E. urograndis* found the value of 4633kcal.kg^{-1} for highest calorificvalue, confirming the data found in this study. Manhães (2008) states in her work that the calorific value of bamboo species is equal or higher of those species commonly used to obtain biomass, such as *Pinus sp.* and *Eucalyptus sp,* featuring as a plant of great prominence in the use as a renewable energy source. The species did not influence in the average values of bulk and energy density of briquettes (Table 1). These results demonstrate that the species used does not interfere in the quality of briquettes, as long as their biomass are under the same granulometric and compacting conditions (pressure and temperature). A few scientific studies have shown the strong effects of variables in the compacting process in the quality of pellets (Liu *et al*., 2014; Carone *et al*., 2011) and briquettes (Gonçalves *et al*., 2013). Quirino *et al*., (2012) found values of 1.00 g.cm^{-3} for briquettes from *Eucalyptus sp* waste, made of fine-grained materials. These values were found for bulk density and are consistent with those presented in this work. Energy density is directly related to the biomass calorific value and the density of briquettes. In this study, the species did not differ statistically in terms of energy density due to the low variation observed in the mean highest calorific value (4515 to 4663 kcal.kg^{-1}) and biomass density (1.13 a 1.20 g.cm^{-3}) of the briquette between species (Table 1). Although statistically equal, there is a smaller numerical value of energy density for *B. tuldoides* (5.14 Gcal.m^{-3}) due to the also numerically lower calorific value (4515 kcal.kg^{-1}) and bulk density (1.13g.cm^{-3}). Therefore, this variable characterizes the importance of biomass densification through the compacting process, in which the denser briquettes present higher energetic densities (Quirino *et al*., 2012). Furtado *et al*. (2010) used a methodology closest to the one used in this study to measure energy density, finding values of 5.4 Gcal.m-³ for briquettes made with pine bark and briquettes made of coconut (4.04 Gcal.m^{-3}), corn cobs (4.17 Gcal.m^{-3}) and passion fruit peel (4.46 Gcal.m^{-3}) respectively, sustaining the data observed in the present work, thus, enabling a more viable comparison as they observe the same parameters, both in regards to briquetting as in the calculation of the energy density.

The results for bulk and energetic densities of briquettes are presented on Table 2, for each studied temperature. As it can be confirmed, briquettes produced under temperatures of 80 and 120ºC have shown higher bulk density values if compared to those produced at room temperature, by 14%. High density of briquettes enables better packing and less expansion, for dense materials are less hygroscopic (Gonçalves *et al*., 2013). A pioneer in evaluating the behavior of lignin, Schaffer (1973) studied the influence of temperature on wood properties, having observed that at 55ºC a process of structural alteration begins, at 85ºC a viscoelastic transition process, and at 120°C lignin starts to soften and lose weight. The absence of statistical differences between bulk density values for the temperatures of 80°C (1.20 g.cm^{-3}) and 120°C (1.22 g.cm^{-3}) indicates that the briquettes of the studied species may be produced at lower temperatures, without compromising this important physical property and reducing energetic costs for its production. According to Chen *et al*. (2009) the temperature increase over 80ºC causes lignin to become plastic, acting as a natural particle binder during the compacting process, making briquettes denser and more resistant. Quirino *et al*. (2012) found values for bulk density of 1.13 and 1.22 g.cm^{-3} for *Eucalyptus sp.* briquettes, produced under the same pressure conditions as stated in the present study, and at temperatures of 130ºC and 200ºC, respectively, thus supporting the data reached in this work. Similarly as observed on bulk density, the energy density was higher in briquettes produced at higher temperatures during the pressing process. As previously discussed, the use of temperature 80°C is recommended if compared to 120°C, as the quality briquettes is not altered, resulting in a reduction of production costs. Lima *et al*. (2011) found values lower than the ones presented in this study, with the compacting of *Eucalyptus benthamii*, (2.22 gcal.m^{-3}.), however using lower compacting pressures. Quirino *et al*. (2012) found values ranging from 4.87 Gcal.m^{-3} to 5.78 Gcal.m^{-3} for briquettes produced from wood waste at high temperatures and under the same pressure conditions, supporting the data in this work. In this context, the greater density of briquettes, the greater their energy density, concentrating energy into a smaller unit of space, highlighting the economic and energetic advantages of the biomass compaction process (Neves *et al*. 2011). The results obtained for volumetric expansion variables, tensile strength by diametral compression and durability are presented on Table 3.

Table 3. Average values for volumetric expansion, tensile strength by diametral compression and durability for bamboo and eucalyptus briquettes. TSDC: tensile strength by diametral compression. Averages followed by the same letter in the column do not differ by Tukey's test at 5% significance

Species	Volumetric Expansion (%)	TSDC (Mpa)	Durability (%)
B. tuldoides	3.25 a (0.58)	2.68 a (0.11)	97.70 a (2.3)
B. vulgaris	2.45 a (0.62)	2.13 b (0.10)	92.70 ab (3.6)
D. asper	2.96 a (0.77)	4.36 c (0.25)	99.60 a (2.8)
E. urograndis	6.21 b (1.23)	1.40 d (0.06)	86.10 b (1.6)

Abbreviations:TSDC = Tensile Strength by Diametral Compression.

The volumetric expansion of briquettes was influenced by the species, ranging from 2.45 to 3.25% in bamboo briquettes and 6.2% in eucalyptus, with a significant difference. The increased expansion in eucalyptus briquettes in relation to bamboo is approximately of 48-61%. Protásio *et al*. (2011) and Silva *et al*. (2015) estimated the compacting of eucalyptus sawdust and found volumetric expansion values of 15.6 and 9%, respectively, 72 hours after briquetting. It is noteworthy that they do not use temperature compacting, justifying the difference found in this study. Tensile strength by diametrical compression suffered significant species effect (Table 3) and was higher in *D. asper* (4.36 Mpa), which may be related to a higher density for this species (1.20 $g.cm^{-3}$), though not significant (Table 1). This variable is essential in assessing the quality of briquettes as it indicates its stackability capacity, impact caused by transportation and abrasion resistance, as briquettes may suffer friction and crumble; as for water absorption, this factor is directly related to where it is handled and stored (Sampaio *et al*., 2007). Silva *et al*. (2015) found mechanical resistance values of 1.20 Mpa in eucalyptus briquettes, and affirmed that higher dimensional stability results in briquettes of higher mechanical resistance, as observed in this study as well. Briquettes produced from biomass of bamboo species showed statistically superior durability values (93 to 99%) compared to eucalyptus briquettes (86%). According to Silva *et al*. (2015) the higher the durability, the more resistant the briquette, thus, the durability test supports the tensile test by diametrical compression, characterizing the mechanical strength of the briquettes. *Eucalyptus* briquettes showed higher volumetric expansion values and lower tensile strength by diametral compression and durability (Table 3). According to a study by Lehtikangas (2001), there is a direct relationship between the amount of lignin and the physical and mechanical properties of the densified material. Literature indicates a lignin content of 22 to 24% for *Dendrocalamus asper,*15% for *Bambusa vulgaris* (Pereira e Beraldo, 2007) and 27 a 31% for several types of eucalyptus clones (Gomide *et al*., 2005), indicating the existing variations among the studied species. Hence, it is recommended to conduct research on the chemical composition of species to evaluate the lignin present in bamboo culms and eucalyptus wood, as lignin is a natural binder, which reorganizes itself internally during the manufacturing process due to high temperatures and pressures, providing the necessary adhesion to promote greater mechanical strength of biofuels. The application of 80°C and 120°C temperature in the production process of briquettes showed lower volumetric expansion and improved tensile strength by diametrical compression and durability (Table 4). For Yamaji *et al*. (2013) the use of heating in pressing may decrease the longitudinal expansion of briquettes when there is no increase in the product's mass. Volumetric expansion values found by Neves *et al*. (2011) and Silva *et al*. (2015) of 15.6 and 9%, respectively, are above those seen in this study, demonstrating the feasibility of temperature usage for the production of briquettes, since volumetric expansion is an important property in the biomass densification process, being inversely proportional to the strength of briquettes. According Souza (2014) the use of higher temperature promotes faster softening of lignin within the biomass, causing particles to adhere more to each other, explaining the higher resistance values observed for temperatures of 80 and 120°C.

Table 4. Volumetric expansion, tensile strength by diametrical compression and durability of briquettes at different temperatures. Averages followed by the same letter in the column do not differ by Tukey's test at 5% significance

Temperature	Volumetric Expansion (%)	TSDC (Mpa)	Durability (%)
± 30ºC	8.24 a (2.7)	0.78 a (0.10)	85.02 a (1.8)
80ºC	1.90 b (0.6)	3.07 b (0.72)	98.69 b (1.1)
120ºC	1.02 b (0.4)	4.07 b (0.81)	98.31 b (2.2)

Abbreviations:TSDC = Tensile Strength by Diametral Compression.

According Karunanithy *et al*. (2012), lignin acts as a thermoplastic substance during briquetting biomass densification, so particles become more adhesive, with possible increases in mechanical properties. Souza (2014) obtained results for tensile strength by diametrical compression between 2.3 to 4.8 MPa in briquettes produced with various biomasses, under the same process conditions (temperature, grain size and pressure), supporting the results obtained in this study. The durability test examines the briquette strength when subjected to conditions impact, falls and abrasions. According to the classification described by Oliveira *et al*. (1992), all results for this variable of different species and different temperatures are considered somewhat friable briquettes, that is, they show good durability and low weight loss when handled. Gonçalves *et al*. (2013) found values between 67.76 to 91.71% for eucalyptus briquettes, a range which includes the species and treatments in studied here. In a study by Liu *et al*. (2014) the durability values found for bamboo pellet range from 95 to 98%, though it is a smaller material than briquettes, these values support those found in this research, as the same methodology was used for that variable. The correlations between briquette properties are shown in Table 5.

Table 5. Correlation between briquette properties. Values in bold = significant at 5% de probability

	BD	ED	TSDC	VE
BD	1.00			
ED	**0.96**	1.00		
TSDC	**0.64**	**0.47**	1.00	
VE	**-0.66**	**-0.58**	**-0.74**	1.00

Abbreviations: Bd = Bulk density; ED = Energy Density; TSDC = Tensile Strength by Diametral Compression; VE = Volumetric Expansion.

A high positive correlation is observed (0.96) between the bulk density and energy density of briquettes was observed. This correlation was already expected since this property evaluates the performance of biomass as a fuel, being defined as the result between highest calorific value and the density of briquettes (Pinheiro *et al*., 2005). Neves *et al*. (2011) state that high-density briquettes are useful for transportation, storage and handling due to optimization and process logistics. Positive and significant correlations were also observed between the mechanical strength, bulk density and energy density with respective variables after the briquetting process (0.47 and 0.64, respectively). This relationship presents itself possibly due to the greater interaction between particles, resulting in higher proximity and surface area of the particles forming the briquettes, creating a denser product, consequently more resistant (Yamaji *et al*., 2013). The volumetric expansion of briquettes showed a high negative correlation with the other variables: (-0.66) for bulk density; (-0.58) for energy density and (-0.74) for mechanical strength. These figures show these variables relevance, as high volume expansions can contribute to a reduction in mechanical strength properties, decreased energy and density of solid biofuels, directly affecting the quality of the material (Neves *et al*., 2011).

Conclusion

- Bamboo briquettes have shown lower volumetric expansion values and higher tensile strength by diametral compression and durability values when if compared to eucalyptus clones, indicating the potential for energetic use as densified material.
- The use of temperature in the bamboo and eucalyptus biomass compacting improved physical and mechanical properties of the briquettes.
- The absence of statistical differences between properties for the two temperatures used in the process indicates that the briquettes of the studied species may be produced at 80ºC, without compromising its quality and reducing the energy costs involved in the production of briquettes.

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