Special Supplement: Bamboo

Characterization of bamboo species and other biomasses with potential for thermal energy generation[1]

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ABSTRACT

Biomass quality is important to strengthen the use of species as reliable energy sources. This study aimed to characterize the energy quality attributes of bamboo species (*Bambusa vulgaris*, *Bambusa tuldoides*, *Dendrocalamus giganteus* and *Guadua angustifolia*) biomass, when compared to other raw materials of residual origin with a high potential for use in thermal energy generation processes (rice husk, eucalyptus chips, coconut husk and fiber). The basic density, higher calorific value and fiber, lignin and ash contents were evaluated. All the evaluated bamboo species present energy quality characteristics equivalent to those of biomasses traditionally used in thermal energy generation, such as high energy density (2,415-2,967 Mcal m^{-3}), high calorific power (4,359-4,568 kcal kg^{-1}), high basic density (0.537-0.653 g cm^{-3}) and low ash content (1.41-2.41 %). The bamboo biomasses of the four evaluated species present adequate characteristics as fuel for thermal energy generation processes, with potential for use in several industrial sectors.

KEYWORDS: Bambusoideae, lignocellulosic material, solid fuel, energy density.

RESUMO

Caracterização de espécies de bambu e outras biomassas com potencial para a geração de energia térmica

A qualidade da biomassa é importante para fortalecer o uso de espécies como fontes energéticas confiáveis. Objetivou-se caracterizar os atributos de qualidade energética da biomassa de espécies de bambu (*Bambusa vulgaris*, *Bambusa tuldoides*, *Dendrocalamus giganteus* e *Guadua angustifolia*), em comparação a outros tipos de matérias-primas de origem residual com elevado potencial de utilização em processos de geração de energia térmica (casca de arroz, cavaco de eucalipto, casca e fibra de coco). Foram avaliados a densidade básica, poder calorífico superior e teores de fibras, lignina e cinzas. Todas as espécies de bambu avaliadas apresentam características de qualidade energética equivalentes às das biomassas tradicionalmente utilizadas na geração de energia térmica, tais como alta densidade energética (2.415-2.967 Mcal m^{-3}), alto poder calorífico (4.359-4.568 kcal kg^{-1}), elevada densidade básica (0,537-0,653 g cm^{-3}) e reduzido teor de cinzas (1,41-2,41 %). As biomassas das quatro espécies de bambu apresentam características adequadas como combustível para processos de geração de energia térmica, com potencial de utilização em diversos setores industriais.

PALAVRAS-CHAVE: Bambusoideae, material lignocelulósico, combustível sólido, densidade energética.

INTRODUCTION

The soils and climate of Brazil make it an ideal location for the expansion of the agricultural and forest biomass industry. Currently, wood and sugar cane are the primary sources of biomass-derived energy in Brazil. Additionally, there is a wide range of degraded areas in the country that are not suitable for the cultivation of normal crops, but are suited to the large-scale planting and cultivation of several bamboo varieties of high commercial value commonly used for biomass production (Santos et al. 2016).

The main biomass source used in energy generation is residual waste of primarily vegetal origin (Marafon et al. 2016). However, some commonly cultivated bamboo species have a high energy potential owing to their high capacity for renewal and rapid growth, and could thus be applied to increase the available sources of biomass used in energy generation, potentially resulting in a high annual increase in biomass production (Balduino Júnior et al. 2016).

Woody bamboos have high growth rates and rapidly produce biomass, and so their cultivation may

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often yield up to 50 metric tons (m^3) of fresh matter per hectare per year (Scurlock et al. 2000), which can be processed to produce a variety of energy-related products (e.g.: charcoal, biogas and biofuels) (Ribeiro 2005, Truong & Le 2014). According to Murakami (2007), the average annual increase in the biomass of bamboo species is 22-44 m^3 ha^{-1} $year^{-1}$, a value far higher than that of pine (25-30 m^3 ha^{-1} $year^{-1}$) and similar to that of eucalyptus (30-40 m^3 ha^{-1} $year^{-1}$) plantations.

Londoño et al. (2002) found that several exotic bamboo species were introduced into Brazil during the Portuguese colonization period, including species of the *Dendrocalamus* and *Bambusa* genera. *Bambusa vulgaris* is a species well-adapted to tropical climates and has thus attracted the attention of the scientific community, especially in the field of biotechnology, owing to its rapid growth and maturation, rigidity and mechanical strength (Drumond & Wiedman 2017).

Bamboo biomass may be used on an industrial scale via direct combustion or the cogeneration of heat and power in both thermoelectric plants and in the construction industry. However, the use of bamboo for combustion, in Brazil, remains limited. Among the species most commonly used, *B. vulgaris* is exemplary, especially in the Northeast region, in the manufacturing of pulp by large companies located in the states of Bahia, Pernambuco and Maranhão. Some of the *B. vulgaris* applications have aroused particular interest, including its use in cogeneration systems in the production of electrical energy and in the pulp and paper manufacturing industries (Guarnetti 2013).

Other species in the Bambusoideae family, besides *B. vulgaris*, also have high growth rates and are excellent alternatives for use in biomass production, with respect to energy generation. According to Bonilla et al. (2010), bamboo is a perennial woody grass that could be used as a potential substitute for wood based on its energy characteristics and high biomass productivity per hectare. Most bamboos are exotic (often having originated in Asia), with numerous species, including *B. tuldoides*, *Dendrocalamus strictus*, *D. giganteus* and *Phyllostachys aurea*, being introduced by the Portuguese in colonial times (Das et al. 2008). These introduced bamboo species are all well adapted to the environments of Brazil (Filgueiras & Santos-Gonçalves 2004). Among them are: *B. vulgaris* (south China), *B. tuldoides* (south Asia), *D. strictus* (India, China and Vietnam), *D. giganteus* (Burma) and *P. aurea* (Asia) (Azzini et al. 1997).

Given that the energy quality of biomasses derived from different raw materials is vital in the development of reliable energy sources, this study aimed to characterize the energy quality attributes of bamboo species, when compared to other biomass sources traditionally used or those with high potential for use in thermal energy generation processes.

MATERIAL AND METHODS

This study was conducted at the Embrapa Tabuleiros Costeiros, in Rio Largo, Alagoas state, Brazil, in 2018. The energy potentials of the biomass derived from four bamboo species (*B. vulgaris*, *B. tuldoides*, *D. giganteus* and *G. angustifolia*) and four other raw materials of residual origin [rice husk, coconut husk (endocarp), coconut fiber (mesocarp) and eucalyptus chips] were assessed.

Samples were taken from specimens of the four bamboo species retrieved from the Germplasm Bank of Bamboo Species (SisGen A2D24A1) of the Universidade Federal de Alagoas (Salvador et al. 2017). Fresh samples were collected for each species by cutting and segmenting each specimen at the median and basal apical portions of the culms, while the agroforestry waste was collected from local processing plants.

Each of the eight types of biomass was characterized by determining its basic density, higher heating value and fiber (cellulose and hemicellulose), lignin and ash contents. The basic density was determined using the NBR 11941 maximum moisture content method (ABNT 2003), while higher heating value analyses were performed using an IKA model C2000 heat pump, after the nibbling of the dry samples. To determine the cellulose, hemicellulose and lignin contents of each sample, samples were dried in an oven at 105 ºC, for 48 h, and ground in a Wiley mill, using a 35 mesh (500 µm) sieve. According to the basic density (Bd) and higher heating value (HHV), the energy density (ED) was calculated according to the equation: ED = Bd x HHV. The percentage of cellulose, hemicellulose and lignin of each material was determined according to the methodology proposed by Goering & Van Soest (1967) and described by Silva (2006). The ash content was determined according to the NBR 8112 standard (ABNT 1986), using 1 g of moisture-free sample, which was incinerated in a muffle furnace preheated to 600 ºC ± 10 ºC. After the complete burning of the samples, they were cooled in a desiccator and weighed using a precision analytical scale.

The used experimental design was entirely randomized, with three repetitions, consisting of 100 g samples. The data obtained were evaluated using analysis of variance (Anova) and their means compared by the Tukey test at 5 % of probability ($\rho \leq 0.05$). All analyses were performed in the Sisvar statistical software (Ferreira 2011).

RESULTS AND DISCUSSION

Significant differences were found in the measured material characteristics among the eight raw material sources (Table 1).

Coconut husk (endocarp) had the highest basic density (0.922 g cm^{-3}) among all the materials evaluated. The basic densities of the culms from the four bamboo species did not differ significantly from one another. The average basic density (0.601 g cm^{-3}) of the bamboo species was significantly higher than that of coconut fiber (0.186 g cm^{-3}), rice husk (0.338 g cm^{-3}) and eucalyptus chips (0.401 g cm^{-3}).

The use of bamboo biomass as a raw material is advantageous, if compared to other biomass sources, as, in addition to the high productivity of the plants themselves, their material is of high density (0.5-0.7 g cm^{-3}) (Lima et al. 2017). According to Brito et al. (1987), the basic density of the tissues of bamboo species of the *Guadua* genus may reach 0.45-0.65 g cm^{-3}, with *Guadua angustifolia* having a density of 0.629 g cm^{-3}. Santos et al. (2016) reported a basic density value of 0.604 g cm^{-3} for *D. asper*, in accordance with our results. However, the density of *B. vulgaris* (0.462 g cm^{-3}) and *B. tuldoides* (0.421 g cm^{-3}) observed here differ from those reported by Santos et al. (2016).

The average for higher heating value of the coconut endocarp (4,784 kcal kg^{-1}) was significantly superior to that of the other materials. The higher heating values of eucalyptus chips (4,586 kcal kg^{-1}) and tissues of *G. angustifolia* (4,568 kcal kg^{-1}), *B. tuldoides* (4,544 kcal kg^{-1}) and *D. giganteus* (4,499 kcal kg^{-1}) did not differ significantly from one another, but were significantly higher than those of *B. vulgaris* (4,359 kcal kg^{-1}), coconut fiber (4,358 kcal kg^{-1}) and rice husk (3,930 kcal kg^{-1}). The higher heating values of *D. giganteus*, *G. angustifolia* and *B. tuldoides* reported here are very similar to those reported by Santos et al. (2016) for *D. asper* (4,526 kcal kg^{-1}) and *B. tuldoides* (4,544 kcal kg^{-1}). However, Santos et al. (2016) found a value (4,662 kcal kg^{-1}) different from the one observed in the present study (4,359 kcal kg^{-1}) for *B. vulgaris*. Moreover, the energy density values of the four bamboo species were superior to the eucalyptus chips, the main raw material used in the thermal energy generation process. For this reason, bamboo species are crops with a high potential for use in the bioenergy production, mainly due to their high fiber and lignin contents, high calorific values and low ash content (Rambo et al. 2015).

With regard to fiber analysis, the cellulose content of eucalyptus chips (59.88 %) was significantly higher than that of rice husk (47.44 %), which, in turn, was significantly higher than that of coconut endocarp (42.91 %). The hemicellulose contents of *G. angustifolia* (42.69 %), *D. giganteus* (40.47 %) and *B. tuldoides* (38.61 %) were higher than those of coconut fiber (33.41 %) and *B. vulgaris* (30.63 %).

Table 1. Average values of basic density (Bd), higher heating value (HHV), energy density (ED) and cellulose (CEL), hemicellulose (HCEL), lignin (LIG) and ash content for each of the eight raw material sources.

Biomass	Bd	HHV	ED	CEL	HCEL	LIG	Ash
	g cm^{-3}	kcal kg^{-1}	Mcal m^{-3}	%			
B. vulgaris	0.638 b*	4,359 c	2,781 b	27.00 c	30.63 b	12.76 c	1.85 c
G. angustifolia	0.577 b	4,568 b	2,636 b	21.01 c	42.69 a	21.47 b	1.71 c
D. giganteus	0.537 b	4,499 b	2,415 b	24.45 c	40.47 a	16.68 b	2.41 c
B. tuldoides	0.653 b	4,544 b	2,967 b	26.48 c	38.61 a	17.92 b	1.41 c
Rice husk	0.338 c	3,930 d	1,328 d	47.46 b	18.82 c	17.39 b	15.3 a
Coconut husk	0.922 a	4,784 a	4,411 a	42.91 b	16.76 c	30.95 a	1.31 c
Coconut fiber	0.186 d	4,358 c	811 d	35.52 c	33.41 b	22.28 b	7.70 b
Eucalyptus chips	0.401 c	4,586 b	1,839 c	59.88 a	17.32 c	17.01 b	0.47 d

* Averages with different letters significantly differ from each other according to the Tukey test at 5 % of probability ($\rho \leq 0.05$).

The lowest hemicellulose values were observed in rice husk (18.82 %), eucalyptus chips (17.32 %) and coconut endocarp (16.76 %).

Coconut endocarp had the highest lignin content (30.95 %) among all the evaluated materials. Among the four bamboo species, *B. vulgaris* had the lowest lignin content (12.76 %), which was reflected in its low higher heating value. Bamboo culm tissues usually mature over a period of one year, in which the lignin and fiber contents of the plant increases. The main chemical constituents of bamboo culms are cellulose, hemicellulose and lignin; however, to a lesser extent, resins, tannins, waxes and organic salts are also present in the culm tissue (Pereira & Beraldo 2007). Moreira (2012), when assessing the chemical constitution of 1-3-year-old *B. vulgaris* plants, reported a mean extractive content of 4.74 %, lignin content of 24.28 % and holocellulose content of 70.98 % (cellulose plus hemicellulose). Additionally, in 3-4-year-old *B. vulgaris* plants, Brito et al. (1987) reported mean holocellulose content of 66.3 %, lignin content of 17.5 % and 16.2 % of extractive content.

The ash content of the bamboo species (1.41-2.41 %) was similar to that of coconut husk (1.31 %) and significantly lower than those of coconut fiber (7.70 %) and rice husk (15.3 %). However, it was higher than that of eucalyptus chips (0.47 %). Santos et al. (2016) observed a similar value for the ash content found in this study in *D. asper* (2.1 %), but their results concerning *B. vulgaris* (2.5 %) and *B. tuldoides* (3.0 %) differed.

The main attributes used to define high-quality biomass, in terms of energy use potential, are: high calorific value, high density, high fiber and lignin content, and low ash content (Marafon et al. 2016). For this reason, the evaluated bamboo species, alongside both the coconut husk and eucalyptus chips, could be considered as excellent raw materials for use in thermal energy generation processes.

It should be noted that bamboo, as well as other biomass sources commonly used in thermal energy generation, often has a high moisture content, and thus requires pre-treatment (including grinding, drying and conversion) before it can be used in energy generation. Lima et al. (2017) reported that the calorific value of materials from different species may vary significantly. Moreover, in order to make viable the use of bamboo as a biomass in thermal energy generation and to become economically competitive, it is necessary to improve production protocols and overcome practical barriers to its implementation through the development of new machinery, especially considering the fact that bamboo harvesting systems in Brazil are not currently mechanized. Thus, current protocols often result in the accretion of large labor and transportation costs.

CONCLUSIONS

1. Biomasses derived from the *Bambusa vulgaris*, *Bambusa tuldoides*, *Dendrocalamus giganteus* and *Guadua angustifolia* species are well-suited for use in thermal energy generation, exhibiting material qualities similar or superior to those of eucalyptus chips, a raw material commonly used in industrial processes;
2. Coconut husk has the highest energy density. The energy density of biomasses derived from the four bamboo species is broadly higher than those of coconut fiber, rice husk and eucalyptus chips;
3. Eucalyptus chips have the highest cellulose content, followed by rice and coconut husk. The hemicellulose contents of *B. tuldoides*, *D. giganteus* and *G. angustifolia* are the highest among all the evaluated biomasses;
4. The lignin content of coconut husk is the highest among all the tested materials. Among the bamboo species, *B. vulgaris* has the lowest lignin content;
5. Eucalyptus chips have the lowest ash content. All four species of bamboo have an ash content similar to that of coconut husk, which is lower than those of rice husk and coconut fiber.

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