Research Article

Energy properties of bamboo biomass and mate co-products

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Abstract
Fossil fuels are being replaced by clean energy sources. Lignocellulosic biomass is considered an eco-friendly alternative, as it is a renewable raw material with high energy potential. In this context, the aim of this study was to determine the biomass energy properties of three bamboo species and mate. Thus, three species of bamboo (*Bambusa vulgaris Var. Vittata*, *Dendrocalamus asper* and *Phyllostachys aurea*) and *Ilex paraguariensis* co-products (branches and sticks) were performed. The particle size, basic density, moisture content volatiles content, ashes content, fix carbon, gross and net calorific value and energy density of these biomasses were evaluated. The biomasses analyzed here were considered suitable for energy purposes, in general, these presented volatile content between 75 and 85 %, fixed carbon content between 15 and 25% and ash content close to 1%. Average fix carbon content of all analyzed biomass was 16.13%. Ash content of *Phyllostachys aurea*, branches of *Ilex paraguariensis* and *Dendrocalamus asper* presented lower values, average of 1.63%. *Bambusa vulgaris* and *Ilex paraguariensis* sticks presented higher values, average of 2.65%. *Phyllostachys aurea* presented gross calorific value higher than, average of 19.35 MJ kg^{-1}. *Bambusa vulgaris*, *Dendrocalamus asper*, *Ilex paraguariensis* branches and sticks presented statistically equal values. *Bambusa vulgaris*, *Dendrocalamus asper*, *Phyllostachys aurea* showed net calorific value higher to the other analyzed materials and did not present statistical difference. Basic energy density of *Phyllostachys aurea* was higher to bamboo species. *Ilex paraguariensis* showed the lowest values with no statistical difference for branches and sticks.

Article highlights

- Knowledge of biomass properties enables the use of residues in bioenergy production as an eco-friendly alternative.
- Bamboo and Mate co-products have desirable characteristics and potential to produce bioenergy.
- The energetic performance of bamboo biomass was superior when compared to the branches and sticks of Ilex paraguariensis.

Keywords Ash content · Energy density · Gross calorific value · Bioenergy

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1 Introduction

Energy consumption has been increasing in recent decades across the globe and, due to the dependence on fossil-based fuels and its high emission of pollutants, the levels of greenhouse gases in the atmosphere also increase [1]. As an eco-friendly alternative, fossil fuels are being replaced by clean energy sources, encouraging a search for more cost-effective renewable fuels and promoting sustainable development [2]. In this scenario, lignocellulosic biomass is considered as a renewable raw material with high energy potential[3].

Despite the bioenergy potential, lignocellulosic biomass is still an unexplored resource. In some cases, if the destination is poorly conducted, it is considered a waste, causing environmental problems such as air pollution (during open burning), water courses pollution and problems in industries, such as occupation of large areas [4]. According to Organization for Economic Cooperation and Development (OECD), Brazil ranked 13th in the CO_2 emitters list. Even with one of the best carbon monoxide compensation energy matrices in the world, the country has pledged to reduce its greenhouse gas (GHG) emissions by more than 35% until 2020 [5], by National Policy on Climate Change (PNMC).

Use of waste in sustainable energy production is an important part of future energy concept. Transforming biomass, an important renewable resource, into bioenergy of low production cost and low emission of acid gases, provides a continuous source of energy, independent of climatic and seasonal changes, in addition, it can be stored and used when needed [6–9].

Brazil has potential for biomass production as an energy source, with the most widely used raw materials being wood residues (shavings and sawdust). However, the proper use of biomass energy resources requires some precautions, such as the shape and size of its particles and biomass high moisture content [10]. Thus, biomass from grass species, agricultural residues and residues from food industry become increasingly important [7], among which we can highlight bamboo species and co-products of mate.

Bamboo is a promising material for energy use [11]. In Brazil there are large commercial plantations, with emphasis on the northeast region and natural fragments in the Amazon interior. In addition, it can be processed with the same equipment used in tree species [12].

Mate (*Ilex paraguariensis* A. St. Hil.) is economically exploited in about 480 municipalities in Paraná states, Santa Catarina, Rio Grande do Sul and Mato Grosso do Sul. It occupies an area of more than 110 thousand hectares, cultivated in approximately 180 thousand rural properties. This culture generates more than 700 thousand jobs [13]; however, two types of waste are largely generated: (1) branches, from the pruning process [14]; (2) thin sticks, from the processing of raw material [15, 16].

Brazilian production of fresh leaves in 2014 was 935 thousand tons [17], around 7% of this material become a co-product of sticks at the end of processing in herbaceous industries. This represents approximately 65 thousand tons per year, of which can be used as an alternative to biomass energy. Energetic properties of biomass are directly related to the energy potential. It is essential to know these properties to optimize production efficiency and improve the quality of the final product, highlighting: basic density, fix carbon content, volatile, ashes and gross calorific value, moisture and ash content, in addition to particle size and shape, moisture absorption capacity and resistance to processing [18, 19].

The energy potential is estimated through the gross calorific value (GCV) and the net calorific value (NCV). GCV is defined as the amount of energy released (per unit mass or volume) in stoichiometric combustion of a combustible material. It basically depends on the chemical composition of each fuel, in general, the higher the GCV, the more efficient the combustion. The study of material energetic properties can be useful in deciding how to use this waste, and suggest it as a potential alternative source of energy.

This study aimed to determine the biomass energy properties of bamboo species and the co-products of mate (branches and sticks of harvesting process).

2 Materials and methods

2.1 Bamboo chip production

Three species of bamboo were used, *Bambusa vulgaris* Var. *Vittata*, *Dendrocalamus asper* e *Phyllostachys aurea*. Thirty individuals were selected with uniformity in height, stem diameter and wall thickness, in addition to a straight geometric shape (to facilitate the chip chipping process) to produce bamboo chips. Mature individuals were selected, aged between three and four years, estimated in their external appearance.

Final dimensions of bamboo chips were approximately 3 mm × 20 mm × 40 mm (thickness, width and length). Subsequently, the material was dried in the open air, in a ventilated environment, until it reached the moisture content.

Figure 1 shows stems harvested, equipment used to produce bamboo chips and quantity of chips produced. Co-products of mate (*Ilex paraguariensis*) resulting from production of herb and/or compost for chimarrão

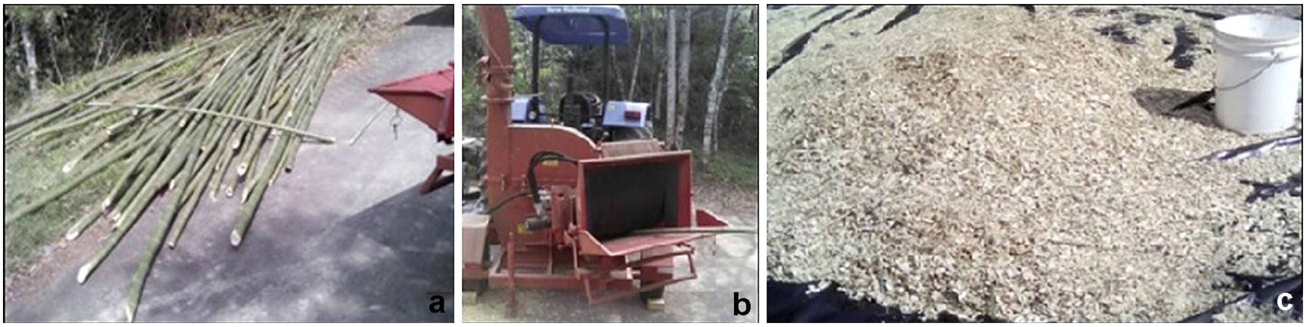

Fig. 1 Bamboo chip production process. **a** Bamboo stems (thirty units); **b** Forest Chipper coupled to the hydraulic system of a farm tractor used to cut bamboo stems into chips; **c** total volume of chips produced

(Brazilian tea) were branches and sticks resulting from the processing of leaves and thin branches.

2.2 Material preparation

Material previously chopped was crushed in a hammer mill (Willye TE 650) and then used in analysis of particle size, proximate chemical analysis, gross and net calorific value and energy density. Three repetitions were performed for each biomass sample, totaling about 1 kg of material (Fig. 2).

2.2.1 Particle size analysis

Biomass of different materials was sieved and separated in three sizes by sieve meshes (< 35, 35–60, > 60 mesh). Material used to determine proximate chemical analysis and calorific value was classified between 35 and 60 mesh, as determined by Brazilian Regulatory Standard (NBR) 6923 [20].

2.2.2 Basic density

Basic density was determined by the hydrostatic method, by immersion in water, as described in NBR 11941 [21].

2.2.3 Moisture content

Samples were placed in an oven at 103 ± 2 °C until constant mass. Moisture (Mc) content was obtained in Eq. (1), by difference between the wet mass (*m1*) and dry mass (*m2*) weight of samples. Moisture content of the samples was determined according to ASTM E 870-82 standard [22].

$$Mc = \frac{(m1 - m2)}{m1} x100 \quad (1)$$

Mc: Moisture content of biomass (%); m1: wet mass (g); m2: dry mass (g).

2.3 Proximate chemical analysis

Proximate chemical analysis was performed according to ASTM D 1762-84 standard [23] to determine the volatiles content, ashes content and fix carbon. Samples of 2.0 g were used in porcelain crucibles. All tests were performed in triplicate.

2.3.1 Volatile content

Volatile content was determined using dry samples, previously kept in oven (Ni 1384 model) for seven minutes at

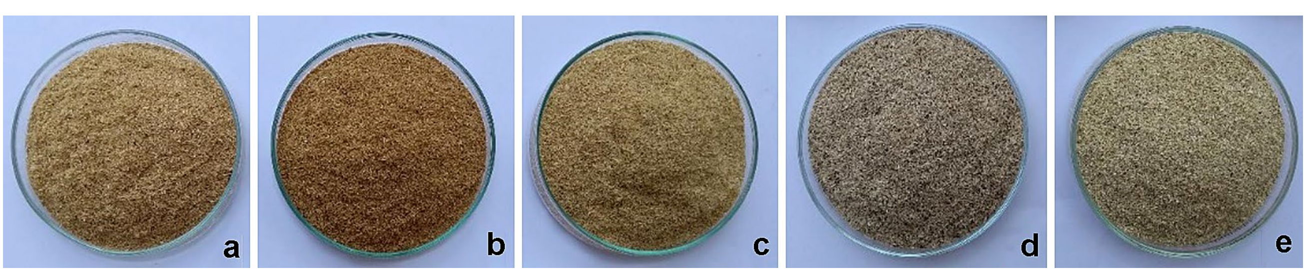

Fig. 2 Alternative materials used in the experiment. Bamboo: Bambusa vulgaris. Var. Vittata (**a**), *Dendrocalamus asper* (**b**), *Phyllostachys aurea* (**c**); mate (*Ilex paraguariensis*): branches (**d**) and thin sticks (**e**)

950 °C. Subsequently, samples were cooled in a desiccator and then weighed.

2.3.2 Ash content

Ash content was determined according to ASTM D 1762-84 [23] standard with the same material used in analysis of volatile content, which were taken to the oven at temperature of 750 ºC, until it reaches constant mass. At the end of this process, it is assumed that only ashes remain inside the crucible, result of combustion of organic components and oxidation of inorganic.

2.3.3 Fix carbon content

Fix carbon content (Fcc) was determined by the difference between values of volatile content and ash content.

2.4 Energetic analysis

Gross calorific value (GCV) was determined according to ASTM D240 [24], using IKA WORKS digital calorimetric bomb, model C 5000. The measurements were taken in duplicates, using an analytical balance for weighing. Net calorific value (NCV) was determined by GCV subtracting the energy used to evaporate the hydrogen constituting the fuel in the form of water.

2.4.1 Energy density

Energy density was determined by the relationship between the value of gross calorific value and the basic density of analyzed materials, by Eq. (2).

$$BED = \frac{(GCV)}{Bd} \div 1000 \quad (2)$$

BED: Basic energy density (GJ m^{-3}); GCV: gross calorific value (MJ Kg^{-1}); Db: basic density (kg m^{-3}).

2.5 Data analysis

Assumptions of data normality and homogeneity of variance were tested, considering the average values obtained from physical, energetic properties and proximate chemical analysis of five alternative lignocellulosic materials, in three repetitions. ANOVA and Tukey mean comparison test at 5% probability of error were performed in a completely randomized design.

3 Results and discussion

Granulometric distribution varied between bamboo and mate species (Table 1). All materials analyzed had volumes between 58.6 and 66.2% in recommended granulometry. Granulometry in class above 60 mesh showed variation between species, with higher values for *Ilex paraguariensis* sticks and *Phyllostachys aurea*, and the lowest value for *Ilex paraguariensis* branches. Highlighting the influence of materials size on the biomass density.

3.1 Basic density, moisture content and proximate chemical analysis

The data relating to basic density, moisture content and approximate analysis are shown in Table 2. It was observed in this study that the biomasses of *Bambusa vulgaris* and *Phyllostachys aurea* had similar basic density, average of 0.624 g cm^{-3}. Followed by *Dendrocalamus asper* with 0.543 g cm^{-3}. Branches and sticks of *Ilex paraguariensis* show similar density, average of 0.406 g cm^{-3}.

Bamboo density average observed in this study corroborate those found by Vale et al. [25] who analyzed *B. vulgaris* in different positions (bottom, middle and top) with one and three years of age. The authors obtained mean values varying between 0.505 and 0.609 g cm^{-3} over height, individuals were studied at three years of age, while Brito et al. [26] reported density 0.687 g cm^{-3}. Berndsen et al. [27] observed that the basic density of bamboo varied with age and position along the stalks, despite its height and total diameter being reached in a short period of time. Melo et al. [28] in a study with *Bambusa vulgaris* in stems, approximately four years old, observed density values close to 0.630 g cm^{-3}. Santos et al. [18] found for *Bambusa vulgaris* var. Vittata 0.462 g cm^{-3}, while for *Dendrocalamus asper*, the values were 0.604 g cm^{-3}. Santin et al. [29] found mean values close to 0.400 g cm^{-3} for basic density of mate pruning branches aged 12–36 months.

Table 1 Distribution of different biomasses in granulometric classes (%)

Raw material	Mesh		
	< 35	35–60[a]	> 60
Bambusa vulgaris	16.2	66.2	17.6
Dendrocalamus asper	18.1	65.5	16.4
Phyllostachys aurea	8.3	64.2	27.5
Ilex paraguariensis (branches)	30.0	58.6	11.4
Ilex paraguariensis (sticks)	12.3	60.8	26.9

[a]35 and 60 mesh materials are recommended for chemical analysis, NBR 6923 [20]

Table 2 Average values of basic density, moisture content and proximate analysis

Materials	Bd	Mc	Fcc	Vc	Ac
Bambusa vulgaris	0.602 a	8.50 a	16.03 ab	81.42 ab	2.55 b
Dendrocalamus asper	0.543 b	8.93 ab	17.16 a	81.04 a	1.80 a
Phyllostachys aurea	0.647 a	9.25 b	15.94 ab	82.61 ab	1.45 a
Ilex paraguariensis (branches)	0.422 c	10.67 c	15.08 b	83.26 b	1.66 a
Ilex paraguariensis (sticks)	0.391 c	8.99 b	16.44 ab	80.80 a	2.76 b

Bd basic density (g cm^{-3}), *Mc* moisture content (%), *Fcc* fixed carbon content (%), *Vc* volatile content (%), *Ac* ash content (%). Averages followed by the same letter do not differ by Tukey test, at 5% probability of error

Carvalho et al. [14] observed a density of approximately 0.400 g cm^{-3} of mate branches.

In comparison with wood species used for energy generation, the density of *Bambusa vulgaris* is similar to those reported by [4], ranging from 0.471 to 0.619 g cm^{-3} for different species of *Eucalyptus*. Santos et al. [18] observed basic density of 0.482 g cm^{-3} for *E. urograndis*, values higher than those verified in this study for mate branches and sticks.

Average moisture content of different materials was 9.27%. All the analyzed materials showed moisture content below 11% and can be used for energy generation [30]. Statistical differences were found between the moisture content in the different species. Lowest moisture content was observed for *Bambusa vulgaris*. Mate branches showed statistically higher humidity values.

However, when analyzing the use of wood residues for energy generation, mean values of moisture content of 16.12% were found for *Pinus* spp wood shavings [31]. Rousset et al. [32] in a study performed with mature culms of *Bambusa vulgaris* species, over three years old. The authors reported values of 20.2% humidity. Lin et al. [33] found values between 6.98 and 7.9% of TU for dry bamboo residues of the genus *Phyllostachys*.

Average fix carbon content of all analyzed biomass was 16.13%. Among the species, there was variation in fix carbon content between species, *Dendrocalamus asper* showed a value significantly higher than other materials and 1.5% higher than the average. *Ilex paraguariensis* (branches) showed a significantly lower value, 2.3% below the average.

Amount of heat generated by waste is determined by fix carbon content. In general, the higher the fix carbon content, the better the quality of material for burning, as this fuel will burn more slowly and with less flame formation [18, 26]. Rambo et al. [11], Vale et al. [25] and Rousset et al. [32] found a fix carbon content of 17.20, 17.66 and 17.75%, respectively, in different bamboo species.

Value of fix carbon content of *Bambusa vulgaris* and *Phyllostachys aurea* observed in this study corroborates those found in the literature [34]. Sette Junior et al. [35] evaluated hybrid of *Eucalyptus grandis* × *Eucalyptus urophylla* and found fix carbon content of 17.5%. These results suggest proximity between the results of fix carbon found in the literature for tree species used in energy forests and the data found in this study, highlighting the biomass of *Dendrocalamus asper*.

Volatile content was higher for mate branches, 83.26%, compared to the sticks, 80.80%. Average values of the different bamboo species did not differ statistically from those found in mate sticks. Bamboo species showed higher volatile content, when compared to the values observed by Rambo et al. [11], Vale et al. [25] and Rousset et al. [32], the authors found values of 81.08, 78.14 and 80.13%, respectively. Sette Junior et al. [35] found 82.2% volatile content for the sample of *Eucalyptus grandis x Eucalyptus urophylla* hybrid.

Volatiles play an important role during the initial stages of combustion, biomass with a high volatile content is easier to ignite and burn. Biomass generally presents high levels of volatile materials [36], despite these combustion advantages, this characteristic can make it difficult to control the combustion process. Pyrolysis and carbonization processes can decrease the volatile content of a biomass. Increase in carbonization temperature favors the maintenance of lower final levels of volatile [37].

Ash content formed two groups. Biomass of *Phyllostachys aurea*, branches of *Ilex paraguariensis* and *Dendrocalamus asper* composed the group with lowest ash content, with an average of 1.63%. The averages of these materials did not differ statistically. The second group was composed of *Bambusa vulgaris* and *Ilex paraguariensis* sticks, an average of 2.65%.

Mate biomass sticks had 2.76% ash content, considered high for an arboreal species. This greater amount of ash can be explained by the young material, presenting a high content of inorganic mineral constituents, necessary for the nutrition of plant portions with intense physiological activity.

Rambo et al. [11] and Rousset et al. [32] in a study with biomass of bamboo species observed ash contents of 1.71 and2.12%, respectively. Moreira (2012) [38] found ash content increasing with age, due to the accumulation of siliceous bodies. Santin et al. [29] in a study with mate branches found mean ash content close to 3.9%. High ash content contributes to the reduction of biomass HCV, considering that it is a mineral content not activated in the combustion process [39]. Sette Junior et al. [35] evaluated hybrids of *Eucalyptus grandis* × *Eucalyptus urophylla* and found ash content close to 0.3%, this value corroborates those found by Santos et al. [18].

Biomass with a high ash content can cause corrosion on the inner wall of boilers, resulting in higher maintenance costs [40]. High ash content decreases calorific value and causes energy loss [41]. Firewood is the solid fuel most used in boilers, with around 1% ash content, a good index for not damaging boilers and furnaces [42].

Knowledge of the proximate chemical analysis composition of biomass provides the material's characteristics as a fuel. Fuels with a low fix carbon content and a high content of volatile materials burn quickly, requiring a short period of time for integral decomposition. Although the ash content has a negative correlation with biomass calorific value [43].

3.2 Energetic analysis

Energy potential was assessed by biomass combustion. Gross calorific value (GCV) and net calorific value (NCV) were estimated. Basic energy density (BED) can also be an indicator of biomass energy potential and corresponds to the product between the gross calorific value and the basic density. Table 3 shows values of the energetic properties of the different biomasses analyzed.

Phyllostachys aurea presented gross calorific value (GCV) superior to other biomasses analyzed, average of 19.35 MJ kg^{-1}. Followed by *Bambusa vulgaris*, *Dendrocalamus asper*, *Ilex paraguariensis* branches and sticks, these values did not differ statistically.

Bambusa vulgaris, *Dendrocalamus asper*, *Phyllostachys aurea* showed NCV superior to the other analyzed materials and did not present statistical difference. *Ilex paraguariensis* sticks and branches showed the lowest NCV values, with an average of 16.28 and 16.13 MJ kg^{-1}, respectively.

Table 3 Average values of the energetic properties of the different biomasses analyzed

Treatment	GCV	NCV	BED
Bambusa vulgaris	17.99 b	16.42 a	10.83 b
Dendrocalamus asper	18.70 ab	16.47 a	10.15 b
Phyllostachys aurea	19.35 a	16.47 a	12.52 a
Ilex paraguariensis (branches)	18.69 ab	16.13 c	7.89 c
Ilex paraguariensis (sticks)	18.75 ab	16.28 b	7.33 c

GCV gross calorific value (MJ.Kg^{-1}), *NCV* Net calorific value (MJ Kg^{-1}), *BED* basic energy density (GJ m^{-3})

Basic energy density (DEb) of *Phyllostachys aurea* was superior to the other analyzed materials, followed by bamboo species *Bambusa vulgaris* and *Dendrocalamus asper*, which did not present statistical difference. Smallest DEb was observed for *Ilex paraguariensis*, with no statistical difference for branches and sticks.

GCV average value corroborates the results found in the literature. Rambo et al. [11], Guarnetti and Coelho [12], Vale et al. [25] and Brito et al. [26] observed values close to 18.32, 16.74, 18.24 and 17.65 MJ kg^{-1}. The found GCV average of 18.94 MJ kg^{-1} for mate pruning branches [29].

Coniferous forest species generally present superior GCV, this occurs due to the higher contents of resin, waxes and oils and mainly of lignin [44]. Wood shavings from *Pinus* sp. and *A. angustifolia* species presented mean GCV values of 17.23 and 17.32 MJ Kg^{-1}, respectively [45].

Biomass GCV correlates with the data obtained from proximate chemical analysis [46]. In general, with the 1% increase in the fix carbon content, there is GCV increase of 0.39 MJ kg^{-1}. In addition, with an increase of 1% in ash content, GCV reduces by 0.2 MJ kg^{-1} [1, 36].

These results help to understand the higher ash content of *Bambusa vulgaris*, which has the lowest GCV. The mineral elements of this species do not contribute to the combustion process, reducing its efficiency. A similar condition is observed in relation to mate sticks.

The found an average NCV value of 17.00 and 16.91 MJ kg^{-1} for *A. Angustifolia* and *Pinus* sp. species, respectively [45]. Observed an average NCV of 18.20 MJ kg^{-1} in saw dust, costan and refills from *Pinus taeda* L. (residues from wood processing) [47].

DEB values observed in this study corroborate the results found in the literature. Santin et al. [29] in a study with mate pruning branches found DEB of 7.57 GJ m^{-3}. Santos et al. [18] in a study with bamboo species and wood of the *Eucalyptus grandis* × *Eucalyptus urophylla* hybrid found an average DEB value of 9.68 GJ m^{-3} and 9.80 GJ m^{-3}, respectively. Moura et al. [47] in a study with harvest residues and wood processing from *Pinus taeda* L. (sawdust, costan and refill), found an average DEB value of 2.98 and 4.81 GJ m^{-3}, respectively.

Biomasses considered suitable for energy purposes, in general, have volatile content between 75 and 85%, fix carbon content between 15 and 25% and ash content below 1% [34, 42]. Bamboo biomass has the potential to produce bioenergy, with high calorific value and low moisture content [11].

The biomasses analyzed in this study showed higher ash content, however adequate values of volatile material and fix carbon, equivalent to that observed for wood from different forest species. These materials tend to have rapid combustion, where most of their mass is burned in the gases form and the lowest proportion in solid form (residual carbon), providing satisfactory energy potential. To reduce the ash content, an alternative is the addition of materials from the wood productive chain in the process of burning, such as forest (harvest) and industrial residues (sawdust, shavings, charcoal fines, etc.).

4 Conclusions

Basic density and fixed carbon content were higher at the bamboo species than in mate biomass. Compared to wood, the average values of the biomasses studied was similar for fixed carbon content and volatile content, on the other hand, it was higher for basic density (only for bamboo species), moisture content and ash content.

Biomasses analyzed here were considered suitable for energy purposes, with values of the main properties close to the energy biomasses found in the literature. Energy analysis showed that the gross calorific value was similar for all biomasses, while net calorific value and basic energy density were higher for bamboo species. Compared to wood species, basic energy density was higher for bamboo and lower for sticks and branches of mate.

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Authors' contributions RUSCH F and HILLIG É conceived and designed the study; RUSCH F and LÚCIO DM performed the study; RUSCH F and HILLIG É analyzed the data; RUSCH F, LÚCIO DM and ABREU NETO R contributed to materials/analysis tools; RUSCH F, HILLIG É, LÚCIO DM and ABREU NETO R wrote and revised the paper.

Declaration

Conflict of interest The authors declare no conflict of interest.

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