

Physical, Chemical and Mechanical Properties of Two-Age *Bambusa tuldoidea* Briquettes

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Abstract: The use of natural resources as an energy source is a well-studied alternative to fossil fuels. Some studies present bamboo as promising biomass for energy generation, and its transformation into briquettes can be a way to take advantage of its production residues. This study's objective was to determine the physical and chemical properties of two bamboo ages (two and seven years old) of *Bambusa vulgaris* species to evaluate biomass quality and its briquettes for energy generation. Regarding the higher heating value, there was no difference between treatments means values, which were 17.8 and 18.2 MJ kg⁻¹ for two and seven years old, respectively, and these values were slightly below those found in the literature for *Bambusa* spp. The mechanical durability was of low quality for both treatments at the testing conditions, so they are not recommended for briquette production. The proximate analysis results were quite near the literature and reinforce bamboo's positive qualities for biofuel usage.

Keywords: bioenergy; wood quality; bamboo

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1. Introduction

Natural resources are sources of alternative energy concerning the decreasing fossil fuel reserves and the world's demographic growth. New biomasses are gaining momentum and are considered as viable, ecological, and sustainable options [1], as they are mostly natural resources, with the potential to generate energy by combustion.

Some studies show the positive characteristics of *Bambusa* spp. for use as biofuel. Two hundred fifty-eight species of bamboo native to Brazil are currently known, distributed in two families of over 12 *Poaceae* subfamilies: *Olyreae* and *Bambuseae* [2].

Bamboo has excellent agricultural potential and can be competitive because it produces annually and is a rustic plant that grows fast and has excellent productivity [3].

The use of bamboo has usually been limited to small businesses for handicrafts and ornaments. Despite these conditions, it is an expanding market in Brazil. However, the tradition in the bamboo production chain is still lacking, and there are knowledge and technology gaps that could allow for the use of different species [4].

Bamboo flowering is generally rare and can take tens or even hundreds of years, depending on the species, making its production harder. A possible alternative is the micropropagation of these species [5].

There is little quantitative information about the area covered with native bamboo in Brazil. A study points to areas that go from about 1.5 million hectares in southwestern

Amazonia, dominated by native bamboo, or close to 11 million hectares if considering the ones where bamboo is present besides other plants [6].

Plantations numbers of bamboo in Brazil are imprecise. The most known private properties that publicize its area sizes point towards 50,000 to 60,000 hectares [7].

The change in the fuel characteristics of a plant, as time goes by, is known mainly for various species, primarily for ash content, density, and higher heating value [8].

Briquetting, in many cases, could be an alternative solution from biomass industrial transformation. Understand its physical and chemical properties may facilitate the understanding of the fuel to be burned and consolidate a new viable supply chain [9].

Chemical properties are related to biomass behaviour when burning in boilers, damaging its structure depending on its characteristics. The formation of slag depends on the chemical elements' ability in the ashes to fuse and how they combine. The formation of fouling is initiated with a sintering process, resulting in tough crusts that are difficult to remove over time. These characteristics are directly related to the material's chemical composition and impair thermal exchange [10]. Physical properties are also relevant; for example, when considering pressed biomasses' ability to withstand handling, transport, and storage, the mechanical durability test has to be a property commonly used to assess briquettes' quality [11].

This study aimed to determine the physical and chemical properties of two different ages of *Bambusa tuldoidea* to assess biomass quality and its briquettes for bioenergy generation.

2. Material and Methods

2.1. Material Collection and Preparation Action

The study was conducted with *Bambusa tuldoidea* biomass. The biomass called "New treatment" (A) is two years old, while the other "Old treatment" (B) is seven years old. Ten sampling points were randomly selected for each treatment, and ten bamboo rods were collected, from which five discs were removed according to the following position: 0%, 25%, 50%, 75%, and 100% of the total height.

A sample of the bamboo rod was separated, weighed using a 0.1 g precision laboratory scale, and taken to oven drying at 65 °C until reaching constant weight. The biomasses were prepared according to Brazilian and American standards [12,13]. After completing the drying process, the biomasses were chopped in a horizontal granulator mill into chips (three millimetres thick), then chopped in the Willey-type mill, and subsequently classified using 40 and 60 mesh sieves with a magnetic sieve shaker to classify the biomasses that were used in the analysis of the physical and chemical properties.

2.2. Physical, Chemical, and Mechanical Properties

The ash content and volatile matter were determined according to the American standards, and fixed carbon content was calculated by the difference between the total mass of the sample and the sum of the ash and volatile material contents [14,15]. The levels of carbon, hydrogen, nitrogen, sulfur, (C, H, N, S), and macronutrients, as well as the higher heating value (HHV), were analyzed in three repetitions for each treatment, using the modified Pregl-Dumas method [16] and the American standard [17], respectively. The biomass retained at 40 mesh sieve was used for briquette production, and its moisture adjusted to 12% on a dry basis.

After adjusting the moisture, 14 briquettes were produced per treatment, weighing 20 g and measuring 35 mm in diameter. A force of 11,550 kgf (1200 kgf cm⁻² pressure) was applied to the sample for 15 s using a hydropneumatic press, and then the density and volumetric expansion were evaluated at 0, 4, 12, 24, 48, and 120 h after pressing.

Logarithmic regression models were adjusted for the expansion of briquettes as a function of time in the form of Equation (1).

$$f_i(t) = a_i \ln(t) + b_i, \quad (1)$$

where a and b are the setting parameters for $f(\%)$, and t (h) is the time elapsed after pressing.

The volumetric expansion rates, which correspond to those derived from the f_i functions, were used as a parameter to define the briquette as stable when they reached $0.02083\% \text{ h}^{-1}$, which corresponds to a rate of $0.5\% \text{ day}^{-1}$, a value here arbitrarily determined, for calculating the moment t , at which stability was achieved using Equation (2).

$$t_i = \frac{a_i}{f_i'(t)}, \quad (2)$$

where t (h) is when the volumetric dimensional stability is achieved, a is the parameter of the adjustment f_i, f_i' ($\% \text{ h}^{-1}$) the rate of volumetric expansion at index i adjustment.

The mechanical durability was evaluated, which is related to the biomass ability to withstand adverse stacking and transport conditions, according to the Comité Européen de Normalisation's technical specifications C.E.N. standards [18] using a rotating chamber constructed into the laboratory.

2.3. Statistical Analysis

For statistical analysis, the statistical program R Core Team was used [19]. After confirming homogeneity of the variance of the residuals according to the Bartlett test [20], and normality by the Shapiro-Wilk test [21], an unpaired t -test was performed, and differences were considered being significant for p -value < 0.05 .

3. Results

For the proximate analysis, significant differences occurred for the averages of ash, being higher for the oldest bamboo treatment. The statistical analysis showed no significant difference between the two treatments for the higher heating value (HHV), volatile matter, and fixed carbon (Table 1).

Table 1. Average ash content, volatile materials, and fixed carbon.

Treatment	HHV * (M.J. kg ⁻¹)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)
A	17.8 (0.2)	1.42 (0.01) ^a	81.56 (0.08)	17.01 (0.08)
B	18.2 (0.3)	1.56 (0.01) ^b	81.24 (0.18)	17.2 (0.18)

* Higher heating value. The superscripted letters present the results of the analysis of variance (at the 95% level). Observations with a different letter are significantly different by unpaired t -test ($p < 0.05$).

Both bamboo ages (two and seven years old) have the same trend results for the macronutrients, following the order of $K > N > Ca > S > Mg > P$, as described in Figure 1.

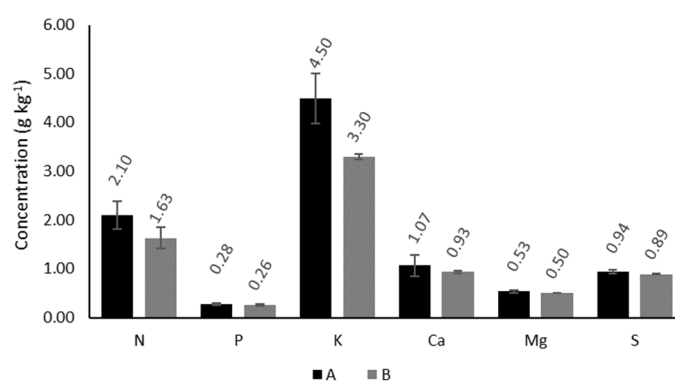


Figure 1. The concentration of six macronutrients in each treatment with standard error.

The unpaired *t*-test showed no statistically significant difference between treatments for the ultimate analysis. The values are shown in Table 2.

Table 2. Average levels of nitrogen, carbon, hydrogen, and oxygen.

Treatment	N (%)	C (%)	H (%)	O (%)
A	0.22 (<0.01)	48.13 (0.02)	5.52 (0.01)	43.76 (0.03)
B	0.22 (<0.01)	47.93 (0.08)	5.52 (0.01)	43.88 (0.08)

The A treatment has the most remarkable expansion, with a final mean value of 24.0% after 120 h, and differs significantly from B with an absolute value of 19.5%.

The logarithmic models' adjustments represent the volumetric expansion of the briquettes for each treatment and are shown in Figure 2 in their graphical form and by their mathematical expressions, where *i* assumes values equal to 1 and 2 for treatments A and B, respectively.

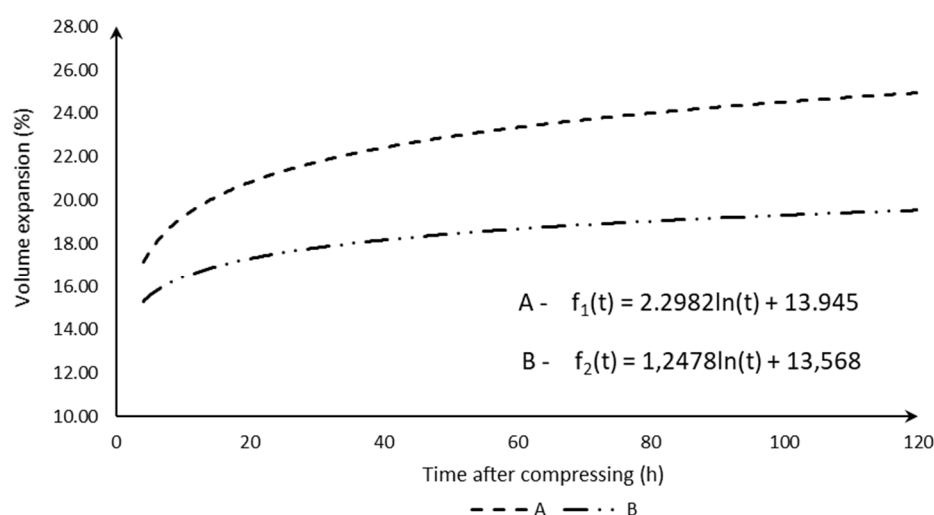


Figure 2. Volumetric expansion of briquettes.

For all treatments, the briquettes' durability was extremely low, according to the standard used classification. Treatments B and A's briquettes crumbled almost wholly. Only a range from 0.89% to 6.18% of the material was retained through the 3 mm sieve. The average values of the results are in Table 3.

Table 3. Results of the mechanical durability test.

Treatment	Mechanical Durability (%)	Moisture (%)
A	2.3 (1.9)	9.3 (0.1)
B	3.1 (1.6)	9.6 (0.3)

Standard errors are in parentheses.

4. Discussion

Ash has an important implication on harvesting or industrial operations. Bamboo ash content varies according to species and management, equal to or less than 1% [22,23]. In the present study, where different bamboo ages were sampled, a higher ash content found is still within limits described [24,25].

Macronutrients influence the melting of ash, such as Ca and Mg, which generally increase the melting point of ash, and K, which decreases it, affecting the sintering process. The level of S can, along with other elements, contribute to the boilers' corrosion [26]. Compared to the average annual values [27], this experiment obtained higher N, P, K, and

Ca values in all treatments. An increasing age led to a decrease in N, P, K, and Ca and increased Mg concentration. The relatively high value of P stands out for being considered an essential element due to its characteristic of facilitating the formation of high melting point K-Ca/Mg phosphate compounds, which, combined with the low ash content, would characterize bamboo as a promising biofuel for not presenting severe sintering at temperatures below 1000 °C [23].

Taking the C, H, and O averages values presented for 50 bamboo species (43.06–46.58% for C, 5.16–7.6% for H, and 46.02–50.35% for O), it can be stated that the values found in this work are either within or very close to those found in the literature [28].

According to Table 1, the HHV values found were slightly lower than those found in the literature. Considering data from several pieces of research, such as mean HHV values of 19.4 MJ kg⁻¹ for *Bambusa* spp [23], mean HHV values were between 19.09 and 19.57 MJ kg⁻¹ for the species *Phyllostachys nigra*, *Phyllostachys bambusoides*, and *Phyllostachys bissetii* [22], and *B. vulgaris*, with an average value of 19.12 MJ kg⁻¹, which is slightly below average [3]. On the other hand, it is possible to track research data with HHV values closer to those of this study, 18.7 MJ kg⁻¹ for *B. tuldoidea*, and 17.6 MJ kg⁻¹ for *B. vulgaris* [29]. HHV of eucalyptus wood (19.0 MJ kg⁻¹) [30] is similar to bamboo, while HHV of rice hulk, wheat straw, timothy grass, and sugar cane bagasse (HHV between 16.3 and 17.3 MJ kg⁻¹) [31–33] is slightly lower. HHV of pinewood is 20.71 MJ kg⁻¹, which is relatively high [34] compared to the HHV of bamboo and the other lignocellulosic species mentioned above.

Although many bamboo properties are similar to eucalyptus, the final average expansion varied from 19.5% up to 24%, which is greater than those of experiments made with eucalyptus [9], which presented an average of 9.7% for the stem of *Eucalyptus urophylla* × *Eucalyptus grandis*. The high expansion and low durability of the briquettes confirm the propositions [35], which suggest that briquettes with greater dimensional stability generally have more excellent mechanical resistance. The briquettes were submitted to the durability test with low moisture, and it is known that this property significantly influences the mechanical durability [36], so this characteristic may have contributed to bad results. The mechanical durability of briquettes fell far short of that recommended by EN 14961-2 [37], requiring a 96.5% durability as a minimum condition for commercialization.

5. Conclusions

As the proximate analysis results show, both treatments had relatively low ash content, so bamboo could be considered suitable for burning in boilers since the lower ash content provides less corrosion and less cleaning time than other biomasses.

The ultimate analysis showed expected results, with no impeditive characteristics for burning the biomass.

There was no difference between treatments regarding the higher heating value, and their values were slightly below those found in the literature for *Bambusa* spp.

Even though bamboo has positive characteristics for burning processes, the two studied treatments' briquettes performed poorly and are not recommended to produce briquettes in the tested condition.

Moisture is a determining factor in the briquette's mechanical durability and may have determined the low mechanical durability.

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