ARTÍCULO

Experimental characterization of briquettes produced from *Eucalyptus* bark with cassava starch binder

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Abstract:
Brazil has a vast area of planted forests, which makes it the second largest producer of bark as a by-product. Several alternatives have been studied for the reuse of this residue; however, little attention has been given to the use of forest residues, such as bark, in the energy sector for briquette production and to the main variables involved in this process. The aim of this work was to evaluate the viability of producing briquettes from *Eucalyptus* bark. The briquettes were produced and characterized according to American and Brazilian standards, evaluating two different particle sizes and the addition of cassava starch. The briquettes produced from *Eucalyptus* bark show potential for use, although attention should be paid to their ash content. In particular, the treatment produced with a 12-mesh granulometry and the addition of cassava starch showed the best chemical, energetic, physical, and mechanical properties. The production of briquettes from *Eucalyptus* bark demonstrates the feasibility of reusing forest residues for bioenergy production.

Introduction

According to IBÁ (2023), in 2023, Brazil had 9,4 million hectares of planted forest for the industry, of which 76 % is *Eucalyptus*. The second largest area of planted forest in the world, after the Russian Federation (FAO 2020). Foelkel (2006) indicates that approximately 9 to 12 % of the tree volume consists of bark, thus generating a large amount of bark.

Thus, there is a large generation of forest residues, and there is still no higher value-added and functional use for this bark.

Several studies are being conducted to find ways to reuse wood bark, such as in the production of extracts for wood preservation, dye absorption for effluent treatment, and production of tannins. There is also a focus on energy purposes, such pellet production (Amari *et al*. 2021, Prayitno *et al*. 2021, Lykidis *et al*. 2023, Litefti *et al*. 2024).

However, little has been seen regarding briquette production. Briquetting aims to form a dense solid from dispersed particles by applying pressure (Miola *et al*. 2020). Souza *et al.* (2022) further complement that briquetting is an efficient process as it concentrates the energy of plant biomass into a smaller volume.

Compared to pellet production, briquettes require less energy during manufacturing and exhibit greater tolerance to variations in particle size and moisture content (Tumuluru *et al*. 2011, Križan 2022).

According to Ferronato *et al.* (2022) between 2012 and 2022, the estimated production of wood briquettes and other densified biomass products increased by more than 20 %. Briquettes have the potential to replace fossil fuels (coal, natural gas, and petroleum derivatives), firewood, and wood biomass. Compared to firewood, briquettes have a higher calorific value, when properly stored and maintaining a moisture content of 10 %,

are easier to transport and store, are cheaper than the others energy fuels and can be produced from waste materials (Arachchige 2021, Kumar *et al*. 2021, Mugabi and Kisakye 2021).

Ribeiro *et al.* (2021) indicates that using waste for briquette production is advantageous because they have low granularity, thus improving the compaction and quality of the biofuel.

To improve the properties of briquettes, binding agents such as cassava and corn starch, quicklime, and tar are added (Fernandez *et al*. 2018). According to Sen *et al.* (2016), the use of cassava starch in briquette production resulted in better physical-mechanical properties and has light weight.

The use of starch also enhances the stability of the briquettes; according to the author, structural integrity was maintained even after six months of storage (Oladeji and Enweremadu 2012).

Despite the numerous advantages of briquette production, little research has been conducted on the production of these products using *Eucalyptus* bark. Given the above, this study aimed to evaluate the physical, chemical, energetic, and mechanical properties of briquettes produced from *Eucalyptus* bark with two different particle sizes, with and without the addition of cassava starch as a natural binder. The research offers innovative insights into the valorization of forestry residues-specifically *Eucalyptus* bark, an underutilized by-product-by exploring sustainable alternatives for bioenergy generation. Moreover, the use of cassava starch as a biodegradable and low-cost binder contributes to advancing environmentally friendly briquette production technologies.

Materials and methods

The bark used was from *Eucalyptus* sp. from southwest of the state of São Paulo. For the evaluation of the briquettes' properties, four treatments were conducted as shown in Table 1. The ashes of the *Eucalyptus* bark were analyzed for inorganic composition in terms of chemical elements. The methodology employed was X-ray fluorescence spectrometry, with semi-quantitative scanning, using a fused bead ($Li_2B_4O_7$ - $LiBO_2$) with the charred ashes of the materials.

Table 1: Studied treatments.

| Treatment	Particle size range (mesh)	Binding agent (%)
T1	5 - 12	0
T2	12 - 35	0
T3	5 - 12	5
T4	12 - 35	5

First, the barks were cut using a band saw and processed in a drum chipper and a Wiley mill, as shown in Figure 1. After processing, the particles were classified according to size, being subjected to sieving using sieves classified as 5 mesh (4 mm), 12 mesh (1,68 mm), and 35 mesh (0,5 mm).

Figure 1: Preparation of the raw material, including (a) cutting with a band saw, (b) drum chipper, and (c) Wiley mill.

For the production of the briquettes, the bark particles had a moisture content of 12 %. 20 g of bark were used for each briquette in treatments T1 and T2, and 19 g of bark and 1 g of cassava starch were used for treatments T3 and T4.

The briquetting process was carried out in a laboratory hydraulic press (Figure 2), in a stainless steel mold with a diameter of 35 mm and a height of 16 mm, without the use of temperature in the process. The production parameters were a compaction time of 5 min, ambient temperature of 25 °C, and a pressure of 1,3 MPa (13 kgf·cm^{-2}).
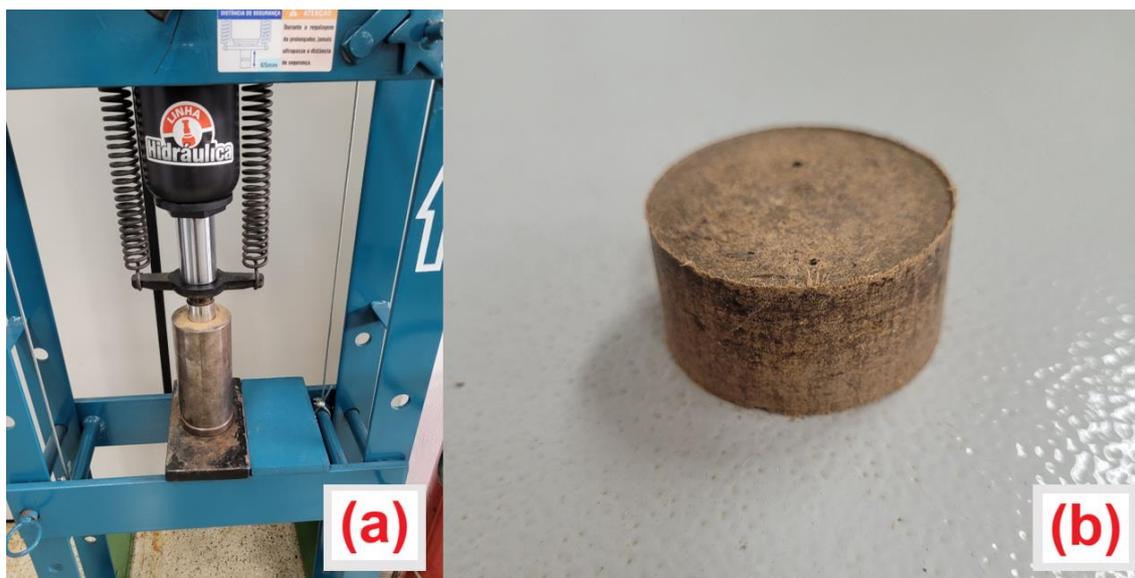
Figure 2: Briquette production, including (a) manual hydraulic press and (b) finished briquette.

For characterization, immediate analysis and calorific power tests were carried out on the raw material, and apparent density, energy density, 24-hour dimensional stability, diametrical compression, and stacking height were performed on the briquettes from each treatment.

The immediate analysis (moisture content, volatile matter, ash content and fixed carbon) and calorific power test were conducted according to standards ASTM E871-82 (2019), ASTM D1102-84 (2021), ASTM E872-82 (2019) and ASTM E711-87 (2023). The apparent density was determined by the ratio of the briquette's mass to its volume, using a caliper with a resolution of 0,01 mm and a precision scale of 0,001 g. The energy density was calculated as the product of the apparent density and the calorific power of the respective mixture.

The 24-hour dimensional stability was determined by the variation in the briquette's volume after its fabrication and after 24 hours. The diametrical compression strength was carried out on the EMIC DL300 universal testing machine, according to the ABNT NBR 7222 (2011) standard, where force was applied to the briquettes until they broke.

Through the maximum force applied in the diametrical compression test, it was possible to obtain the maximum number of briquettes to be stacked (Equation 1) and the maximum stacking height of the briquettes (Equation 2).

$$N_{emp} \frac{F_{max}}{f_s m} \quad (1)$$

Where: N_{emp} is the number of briquettes in the stack, F_{max} is the maximum breaking force (kgf), fs is the safety factor, and m is the mass of the briquette (kg).

The mass used was the nominal mass of the briquettes of 20 g, and the safety factor was 3,0.

$$h_{emp} = N_{emp} d \quad (2)$$

Where: h_{emp} is the maximum stacking height of the briquettes (m) and d is the diameter of the briquette (m). The diameter used was the nominal diameter of 3,5 cm.

At the end of all tests, Shapiro-Wilk tests were conducted to check the normality of the data, and Bartlett tests were conducted to check the homogeneity of variances. Subsequently, ANOVA was performed to verify if there was a statistical difference, and, when necessary, the Tukey test was conducted using R software version 4.2.2, significance level used in the tests ($\alpha = 0,05$).

Results and discussion

Table 2 presents the quantitative elemental chemical composition of metals contained in *Eucalyptus* bark ashes. The elements sodium, zinc, and barium had concentrations lower than 0,0001 % in the analysis. Among the metals with the highest concentration, calcium had a value much higher than the others.

Table 2: Results of the quantitative elemental chemical composition in the bark ash.

Chemical element	Mass quantity (%)
Calcium	83,119
Potassium	3,935
Magnesium	3,115
Iron	2,658
Silicon	2,100
Manganese	1,573
Aluminum	1,162
Sulfur	1,123
Strontium	0,545
Titanium	0,386
Copper	0,205
Bromine	0,076
Nickel	0,003

Table 3 presents the results of the immediate analysis, containing the average ash content, volatile materials, and fixed carbon of the briquettes for each treatment and for the cassava starch used.

Table 3: Results of the immediate analysis.

Treatments	Ash content (%)	Volatile matter content (%)	Fixed carbon content (%)
T1	9,04	75,84	15,12
T2	12	78,26	9,74
T3	8,60	76,74	14,66
T4	11,41	79,04	9,54
Cassava starch	0,18	93,97	5,85

The treatments with smaller particle size (12-35 mesh) showed a higher ash content, but all values were high compared to *Eucalyptus* wood, which has up to 1 % ash content. Ash content was higher in the treatments with smaller particle sizes, as compaction was greater, resulting in a higher amount of bark within the same volume. This ash is mainly composed of calcium, with smaller proportions of potassium and magnesium. A high ash content reduces the calorific value since mineral compounds do not generate energy during combustion and can lead to boiler wall thickening with ash accumulation, increasing maintenance needs (García *et al*. 2014, Sabatti *et al*. 2014).

Table 4 presents the results of the energy tests of the briquettes, containing the mean, standard deviation, and statistical analysis, where equal letters horizontally do not have statistical difference at the 5 % significance level. For the binder, the determined higher calorific value was 17,162 (85,24) MJ·kg^{-1}.

Table 4: Results of the energy tests.

Energy tests	T1	T2	T3	T4
Moisture content (%)	9,87	12,03	9,96	10,01
High heating value (MJ·kg^{-1})	16,415 A (0,298)	15,844 B (0,094)	16,453 A (0,283)	15,910 AB (0,089)
Low heating value (MJ·kg^{-1})	15,059 A (0,298)	14,487 B (0,094)	15,096 A (0,283)	14,553 AB (0,089)
Energy density (MJ·m^{-3})	17665 A (520)	16578 C (271)	17954 A (383)	17051 B (182)

The treatments produced with larger particle sizes showed a higher value of high calorific value and energy density, which is due to the lower ash content presented by the samples, Treatment 3, with the addition of cassava starch, showed slightly superior results compared to the treatment without starch.

The high heating value obtained from *Eucalyptus* bark in the four treatments of this study showed lower value compared to *Eucalyptus* wood found in other studies. Nakashima *et al.* (2017) obtained higher heating values for *Eucalyptus* wood in the range of 17,690 MJ·kg⁻¹ to 19,490 MJ·kg⁻¹.

Table 5 presents the results of the physical-mechanical tests of the briquettes, containing the mean, standard deviation, and statistical analysis, where equal letters horizontally do not have statistical difference at the 5 % significance level.

Table 5: Results of the physical-mechanical tests.

Physical-mechanical tests	T1	T2	T3	T4
Apparent density (kg/m³)	1174 A (35)	1146 B (19)	1191 A (25)	1173 AB (13)
Dimensional stability 24h (%)	7,89 A (0,63)	7,12 A (0,59)	7,26 A (0,72)	6,91 A (0,86)
Diametrical compression stiffness (MPa)	26 A (7)	18 B (1)	32 A (3)	20 B (4)
Diametrical compression strength (MPa)	1,66 B (0,40)	1,18 C (0,06)	2,09 A (0,15)	1,40 C (0,21)

The apparent density of the briquettes was higher in the treatments with smaller particle size (12-35 mesh), because the smaller particle size of the material facilitate densification. Dimensional stability did not show significant differences between the treatments.

Treatments with higher densities showed greater mechanical strength and stiffness, the same was observed by Wilczynski *et al.* (2021).

Regarding diametrical compression, briquettes produced with *Eucalyptus* wood showed a strength of 0,50 MPa, which is lower than the value found in the present study (Nakashima *et al*. 2017).

Table 6 presents the stacking characteristics of each treatment, containing the mean maximum breaking force (F_{max}), the number of briquettes in the stack (N_{emp}), and the maximum stacking height (h_{emp}).

Table 6: Stacking characteristics of the briquettes.

Treatment	$F_{máx}$ (kgf)	N_{emp}	h_{emp} (m)
T1	165,3	2755	96
T2	116,4	1940	68
T3	205,4	3423	120
T4	123,1	2051	72

The treatment with the lowest mechanical strength and lowest stacking height was Treatment 2, produced with 35-mesh bark and without the addition of an additive, with a maximum height of 68 meters. In contrast, treatment 3, produced with 12-mesh bark and the addition of cassava starch, achieved the highest strength and maximum stacking height (120 m).

Storage sheds typically have heights ranging from 10 to 15 meters from the floor to the roof, so all treatments have excellent stacking conditions.

Conclusions

The production of biomass briquettes from *Eucalyptus* bark is feasible, particularly when appropriate particle sizes and natural binders are used.

The briquettes produced from *Eucalyptus* bark exhibited good quality, with a high content of volatile materials and fixed carbon, but also a high ash content. Therefore, it is necessary to pay attention to their use on an industrial scale by performing periodic maintenance on burning equipment.

The energy properties of the briquettes were satisfactory, as well as the physical-mechanical properties, presenting values similar to those of *Eucalyptus* wood briquettes. The briquettes have sufficient strength for stacking from the ground to the top in storage sheds and good dimensional stability.

Notably, the briquettes produced from *Eucalyptus* bark with a 12-mesh particle size and the addition of cassava starch exhibited the best chemical, energetic, physical, and mechanical properties.

These results indicate the potential for using forest residues in higher value-added products, in addition to bioenergy production.

Author contributions

M. F. F. S.: Conceptualization, data curation, formal analysis, methodology, writing – original draft, writing – review & editing. C. K. C. A.: Conceptualization, data curation, methodology, writing – original draft. J. V. F. S.: Data curation, methodology, validation, writing – review & editing. G. A. P.: Data curation, methodology, writing – review & editing. F. S. R.: Validation, writing – review & editing. E. A. M. M.: Conceptualization, supervision. M. G.: Conceptualization, supervision. J. C. C.: Conceptualization, data curation, writing – review & editing, supervision.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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