Industrial Crops & Products 122 (2018) 209–213

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Energy enhancement of the eucalyptus bark by briquette production

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ARTICLE INFO

Keywords:
Wood
Granulometry
Densification

ABSTRACT

The aim of this article is to evaluate the use of eucalyptus bark, in the form of briquettes, as an energy source. Bark of a *Eucalyptus grandis* x *Eucalyptus urophylla* (*E. urograndis*) hybrid was obtained from the processing (debarking) of eucalyptus poles before industrial preservation treatment. For comparison purposes, wood discs were cut from the same poles. Two conditions of granulometry of the bark (crushed and crushed + milled) were separated to verify the effect of the particle size on the quality of briquettes. Biomass of the bark and wood, in its natural form, were evaluated and briquettes were produced for energy and physic-mechanical characterization. The direct application of bark in its natural form, as a source of bioenergy, presents disadvantages when compared to the wood, due to the high ash content and the low heating value. The *E. urograndis* wood and bark biomass residues can be used as a source of raw material to produce high quality briquettes. It was possible to verify a gain of the energy density through the process of briquetting, when compared to the raw biomass, as well as an improvement on the physic-mechanical characteristics.

1. Introduction

The participation of renewable energy in the Brazilian energy matrix has shown continuous growth over the years, reaching 43% at the end of 2016 and can be attributed to the good performance of hydroelectric, wind, and biomass generation (MINISTÉRIO DE MINAS E ENERGIA, 2016). In this scenario, Brazil has the potential to increase the share of biomass in the energy matrix, among other factors, due to the large amount of residues generated in the agricultural and forestry sectors, both in the field and in the industry.

In the forest-based industries, it is estimated that the generation of wood residues was approximately 13.8 million tons in 2016, with 66% used in the generation of energy and 24% processed into chips and sawdust. Most of the wood used (wood chips, wood-based panels, paper and cellulose) depends on the removal of bark from logs during the industrialization process (Lopes et al., 2016). These activities that depend on debarking, represent 78% (151 million m^3) of the industrial wood consumption in Brazil in 2016 (Indústria Brasileira de Árvores – IBÁ, 2017). Therefore, bark is a significant residue from the processing of eucalyptus wood.

The direct use of the residual biomass in a natural form, for energy purpose, presents some unfavorable characteristics related to the high moisture content, hygroscopic nature, varied dimensions and volumes, and low mass and energy density (Araújo et al., 2016; Hansted et al., 2016). One of the possibilities for reducing or eliminating the main problems associated with the direct use of biomass is through compaction processes, such as pelletization and briquetting (Sette et al., 2016).

The characteristics and quality of the briquettes can be influenced by variables related to the raw material (granulometry, chemical composition of the biomass, moisture content, etc.) and to the production process (pressure, temperature, etc.) (Nakashima et al., 2017; Zhang et al., 2018). The study of the effects of these variables on the quality of the briquettes is important, as it can present solutions regarding the energy demand, mainly on the use of the residual raw material for industrial processes.

The energy utilization of the residues and their application in the form of briquettes can be evaluated with parameters such as apparent and energy density, durability, mechanical strength by diametral comprehension, and volumetric expansion (Sette et al., 2016; Freitas et al., 2016; Castro et al., 2017). These parameters will determine the characteristics of the biomass and the best technique that can be used

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https://doi.org/10.1016/j.indcrop.2018.05.057
Received 28 September 2017; Received in revised form 17 May 2018; Accepted 21 May 2018

on the briquettes for energy uses (Eufrade et al., 2017).

Scientific studies have evaluated residues of forest and agricultural species (Paredes-Sánchez et al., 2016; Castro et al., 2017; Bentsen et al., 2018) and in their densified form (Moreno-Lopez et al., 2017; Gryazkin et al., 2017) for energy generation. However, studies focused exclusively on the bark, mainly of the eucalyptus, are still scarce; noteworthy are the studies of Eloy et al. (2016). In this context, the aim of this article was to evaluate the use of eucalyptus bark as an energy source in the form of briquettes.

2. Material and methods

2.1. Area characterization, sample collection and preparation

Eucalyptus grandis x *Eucalyptus urophylla* (or *E. urograndis*) bark was obtained from the processing (debarking) posts, before the industrial preservative treatment. The posts (2.20 m long) were cut from seven-year-old trees of commercial planting, located in the central region of the state of Goiás in Brazil (16°18′28.85″S and 49°13′3.80″W), with an altitude of 852 m. The climate was classified as Aw, according to Köppen, with wet and rainy summers (October to April) and dry and relatively cold winters (May to September).The average annual rainfall was 1432 mm, and average temperature was 20.4 °C and 24.4 °C in the colder and warmer months, respectively.

The eucalyptus bark was crushed and transformed into sawdust using a shredder. Part of the crushed bark biomass was separated and the remaining material was milled with Willey-type knives. This separation was performed to evaluate the effect of the biomass particle size on the characteristics of the briquettes. The two treatments with the eucalyptus bark comprised of: crushed (C) and crushed and milled (C + M).

Discs of wood were cut from the same *E. urograndis* posts used to obtain the bark and were crushed in a grinder and milled with Willey-type knives.

2.2. Biomass characterization

The samples of eucalyptus wood and bark that were crushed and milled underwent a mechanical separation with an international sieve No. 24 (American Society For Testing and Materials, 1982, of 60 mesh, in the orbital shaker. From the milled biomass in the 60 mesh, the high heating value (HHV) was determined by calorimeter, according to ASTM (American Society for Testing and Materials), ASTM D5865-13, and the volatile matter, ash and fixed carbon contents as recommended by ASTM E872-82 and ASTM D1102-84.34. The bulk density was evaluated according to according to ABNT (Brazilian Association of Technical Standards), ABNT NBR 11941, and the granulometric profile, were determined for the biomass bark in two conditions (crushed and crushed + milled) and wood in the crushed + milled condition. The energy density was obtained by multiplying the high heating value by the apparent density of biomass.

2.3. Briquette production and characterization

For the production and characterization of the briquettes of eucalyptus bark and wood, the biomass was used under the following conditions:

a) Bark: crushed (C) and crushed and milled (C + M)
b) Wood: crushed and milled (C + M)

The biomass of bark and wood were dried at 105 °C (± 2 °C) until constant weight and the moisture content adjusted to 12%, using a water sprayer and a precision weighing balance, as proposed by Silva et al. (2015). The moisture content of 12% is considered ideal for briquettes manufacturing (Nakashima et al., 2017; Eufrade et al., 2017).

The compaction of the urograndis bark and wood biomass in the form of briquettes was carried out in a laboratory machine with a pressure of 13.7 MPa, at 120 °C, for five minutes, followed by a cooling time of 10 min, under forced ventilation. The briquetting conditions were experimentally defined from preliminary tests of pressing and cooling time, choosing those in which the briquettes presented the best compaction. The pressure exerted was within the range used by several studies (Quirino et al., 2012). For each briquette, 40 g of milled biomass was used, to finally obtain a briquette of approximately 4 cm in length and 3 cm in diameter, producing 15 briquettes for each condition (C bark, C + M bark and C + M wood), with a total of 45 briquettes.

The apparent density of the briquettes was obtained through Eq. (1).

$$d_{ad} = \frac{Mi}{\pi * r^2 * h} \tag{1}$$

Where:

D_{ad} = apparent density (kg m^{-3})
M_i = initial weight of the briquettes at 12% of moisture content (kg)
r = briquettes radius (m)
h = briquettes height (m)

The volumetric expansion of the briquettes was calculated by measuring the height and diameter, with the aid of the digital caliper, at two different times: (i) immediately after the briquetting and (ii) at 72 h after the briquetting; the necessary time for the dimensional stabilization of the briquettes. This period was chosen due to the records in the literature regarding stabilization of the volumetric expansion of the briquettes (Hansted et al., 2016).

The diametric compression tensile strength was calculated using a universal test machine: EMIC-DL30000, with a 500 kgf load cell at a constant speed of 0.3 mm min^{-1} (Quirino et al., 2012), where a load in the transverse direction was applied on the samples. The test was carried out from an adaptation of ABNT (Brazilian Association of Technical Standards), ABNT NBR 7222 that was proposed to determine the tensile strength by diametrical compression in cylindrical samples of concrete and mortar.

The durability of the briquettes was determined by mass loss, as described by Toscano et al. (2013) and Liu et al. (2014), using Eq. (3). The briquettes were weighed to obtain the initial mass and taken to a vibrating sieve for 10 min, at 80 rotations per minute. After this procedure, the briquettes were again weighed, and the final mass was obtained.

$$Dur = \left[\frac{m_{fd}}{m_{id}} x100\%\right] \tag{3}$$

Where:

Dur = durability (%)
m_{id} = briquettes initial mass (g)
m_{fd} = briquettes final mass (g)

The energy density was calculated by multiplying the high heating value of the biomass by the apparent density of each briquette, according to Eq. (4).

$$ED = HHV * AD \tag{4}$$

Where:

ED = energy density (kJ m^{-3})
HHV = HHV (kJ m^{-3})
AD = apparent density (kg m^{-3})

The HHV of the samples were also calculated before and after the briquetting process, in order to verify if the briquetting process affects the heating generation.

2.4. FTIR

The spectroscopic characterization of the biomasses (bark and wood) was performed before and after briquetting. It was analyzed the absorbance signal in the Fourier transform infrared spectroscopy (FTIR)

Table 1
Characteristics of *E. urograndis* bark and wood biomasses, crushed and milled.

Biomass	VM (%)	FC (%)	AC (%)	HHV (kJ kg^{-1})	BD (kg m^{-3})	ED (kJ m^{-3})
Bark	79.1* (0.3)	17.3 (0.8)	3.6* (0.7)	16401* (607)	250 (10)	4.14 × 10^{6}*
Wood	83.1 (0.2)	16.7 (0.9)	0.3 (0.3)	19485 (828)	260 (20)	5.10 × 10^{6}

VM = Volatile Matter; FC = Fixed Carbon; AC = Ash Content; HHV = High Heating Value; BD = Bulk Density; ED = Energy Density. Means are followed by standard deviation. Student *t*-test: *$p < 0.05$.

apparatus.

2.5. Data analysis

Prior to data analyses, outliers, data distribution and variance heterogeneity were evaluated. The statistical analysis was performed based on a completely randomized design. For all variables, the averages and standard deviation were obtained. Averages were compared with t-Student test, 5% significance, to verify the effect of biomass and granulometry.

3. Results and discussion

3.1. Biomass characterization

The results of the proximate analysis, high heating value, bulk density, and energy density of the bark (C + M) and wood (C + M) of *E. urograndis* are presented in Table 1.

The content of volatile materials was significantly higher in wood (83.1%) than in bark (79.1%) and the fixed carbon content did not differ between biomasses, with a mean value of 16.7% for wood and 17.3% for bark. The results are similar to those presented by Eloy et al. (2016) for the bark of *E. grandis* and *E. urograndis*, respectively, and by Sette et al., (2016) for *E. urograndis* wood.

The ash content was significantly higher for the bark (3.6%) than for the wood (0.3%). Other scientific studies that evaluated the energy characterization of bark and wood in several forest species, including eucalyptus, also found higher ash content for bark. This could be explained by the higher concentration of mineral nutrients in the bark compared to wood (Eloy et al., 2016; Khabibi and Irawan, 2016).

High ash content presents a problem in its use for direct burning processes (Khabibi and Irawan, 2016), which are necessary in the boilers with rotating grates. Ash is a relevant parameter for the design of the boiler and for its cleaning. The combustion of biomass with high levels of ash will require a more regular and effective removal process. Ash is abrasive and, in the long term, can cause corrosion of the metallic elements in the burners (Liu et al., 2014).

The average high heating value found in the bark was 16401 kJ kg^{-1}, being statistically lower than that found in wood (19485 kJ kg^{-1}). The average values found and the differences in the contents of the two eucalyptus biomasses were according to the literature (Freitas et al., 2016). As previously mentioned, the reduction in the high heating value in the bark when compared to wood may be associated with the high ash content in the bark (Eloy et al., 2016), as also observed in this study.

It was possible to verify that the briquetting of the biomass did not affect the HHV of the samples. It was performed a test before and after the briquetting. T student test was performed, and the results made it possible to claim that the HHV remains the same, Table 2.

Table 2
HHV of the samples before and after the briquetting process.

HHV	J g^{-1}
Wood after briquetting	18631 (± 423)
Bark after briquetting	16432 (± 176)
wood before briquetting	19120 (± 211)
bark before briquetting	16490 (± 266)

There was no effect of biomass (bark and wood) on bulk density, with average values of 250–260 kg m^{-3}. This result can be explained by the characteristic of the biomass used in the determination of the bulk density, both crushed and milled. The values found are within the minimum values for use in energy generation. Santiago and De Andrade (2005) evaluated the mechanical processing residues of *E. urophylla* wood of seven-year-old trees, and found a bulk density ranging from 190 kg m^{-3} for the bark and 280 kg m^{-3} for the wood biomass.

The energy density was statistically lower in the bark (4.13 × 10^{6} kJ m^{-3}) than in wood (5.10 × 10^{6} kJ.m^{-3}). This difference is associated with the differences in high heating values (lower in the bark), as the bulk density did not change according to the biomass (Table 1). The energy density indicates the amount of energy stored per volume of material (Sette et al., 2016). The energy density of the wood biomass and *E. urograndis* bark can be considered low in comparison to other sources. One of the methods to increase the biomass energy density is to increase the concentration of energy per unit volume, for example, from biomass densification process (Sette et al., 2016; Castro et al., 2017; Sova et al., 2018).

3.2. Energy and physic-mechanical characterization of briquettes

Briquettes were produced with the biomass of bark in two conditions (crushed + milled and only crushed) and the wood crushed and milled. The evaluation of the granulometric distribution of the three materials used indicates the differences. The biomass of the only crushed bark was mostly represented by particles retained in 20 mesh (0.85 mm), with ~70% of the total, while the crushed and milled biomass presented particles of 60 (0.25 mm) and 100 mesh (0.15 mm) (90%), both for bark and wood (Fig. 1). Despite the differences between the crushed and crushed + milled biomass particles, all the material used was classified as ‘fine’ (Bergström et al., 2008; Quirino et al., 2012), as it was below 1 mm.

First, it was compared the quality of the briquettes produced from bark and wood of *E. urograndis* in the same granulometric conditions (crushed and milled; C + M). The objective is to determine the viability of the bark as raw material in comparison to wood, which is traditionally used for the production of densified materials (Table 3).

The average apparent density of bark and wood briquettes did not differ statistically (1340 and 1320 kg m^{-3}, respectively), probably due to the similar density of the two biomasses (Table 1) and the same conditions of the briquetting process. These apparent density values are within the range of values from the literature, under the same conditions of briquetting (temperature, time, and pressure) for wood

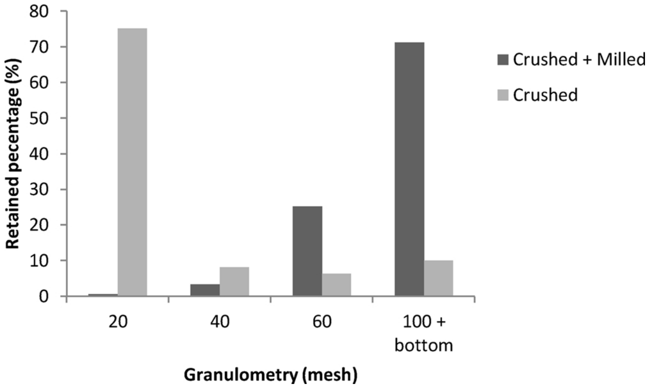

Fig. 1. Granulometric percentage of bark and *E. urograndis* wood.

Table 3
Energy and physico-mechanical briquettes characteristics of the bark crushed and milled (C + M), crushed (C), and wood (C + M) of *E urograndis.*

Biomass	Apparent Density ($kg\,m^{-3}$)	Energy Density ($kJ\,m^{-3}$)	RTDC (MPa)	Durability (%)	Volumetric Expansion (%)
Bark C + M	1340 (110)	22.09×10^6	4.70* (0.30)	99.67 (0.07)	1.56 (0.12)
Bark C	1310 (91)	21.46×10^6	4.33 (0.40)	99.70 (0.08)	2.01 (0.10)
Wood C + M	1320 (102)	25.52×10^6	4.40 (0.40)	99.51 (0.18)	1.03 (0.08)

RTDC = Resistance to Traction by Diametric Compression. Means followed by standard deviation. Student *t*-test: * $p < 0.05$.

briquettes of *E. urograndis* (Freitas et al., 2016).

The average energy density of *E. urograndis* bark briquettes was lower ($22.09 \times 10^6\,kJ\,m^{-3}$) than those from wood briquettes ($25.52 \times 10^6\,kJ\,m^{-3}$). This difference can be explained by the higher calorific value observed for wood when compared to bark (Table 1), resulting in a higher energy density, as was also observed in other scientific studies (Sette et al., 2016, Freitas et al., 2016) for briquettes of *E. urograndis* wood.

These results show that the densification of the biomass, through briquetting, increases the energy density, with increments in the order of five times (from 4.14×10^6 to $22.09 \times 10^6\,kJ\,m^{-3}$ for bark and from 5.10×10^6 to $25.52 \times 10^6\,kJ\,m^{-3}$for wood). Therefore, the greater the apparent density of the briquettes, the greater its energy density, as energy is more concentrated in a unit of volume, highlighting the economic advantages of the compaction process of the biomass. Quirino et al. (2012) found similar values when evaluating briquettes of eucalyptus residues, in the same experimental conditions of the present study, varying from 20.37×10^6 to $24.18 \times 10^6\,kJ\,m^{-3}$; and Sette et al. (2016), evaluating the energy density of *E. urograndis* wood, of six-year-old trees, found a value of $26.61 \times 10^6\,kJ\,m^{-3}$.

Regarding the resistance to traction by diametric compression (RTDC), the briquettes produced with bark showed an average of 4.70 MPa and those produced with wood, 4.40 MPa, with no statistical difference. This result reflects the similarity between the bulk densities. As indicated by Quirino et al. (2012), the RTDC is directly related to the bulk density of briquettes, as can be observed in the present study. The RTDC is one of the most important properties in evaluating the quality of briquettes, as it indicates the capacity of stacking, and the impact caused by transportation. Briquettes suffer friction and can crumble during transportation, potentially causing abrasion. RTDC also determines water absorption, which has a direct relationship with the place where it is handled and stored (Hansted et al., 2016).

The durability test is complementary to that of RTDC (Silva et al., 2015) and analyzes the resistance of the briquette when subjected to conditions of falls, impacts, and abrasions. The average durability values of 99.7% for bark and 99.5% for wood, observed in this study (Table 3), indicate that bark and wood briquettes of *E. urograndis* are of low friability, presenting good durability and low mass loss when handled. Other studies have found similar values (Freitas et al. 2016; Sette et al., 2016).

Volumetric expansion was statistically higher for bark (1.56%) than for wood (1.03%) briquettes of *E. urograndis* (Table 3). According to Silva et al. (2015), humidity and the chemical composition of the biomass are the main factors for volumetric expansion of the briquette. Holocellulose, lignin, and the extractives contents, not evaluated in this study, can influence water absorption. Thus, to understand the hygroscopic behavior of bark and wood and their differences, chemical analyses are recommended.

To evaluate the effect of the particle sizes of the bark biomass (granulometry) and the quality of the *E. urograndis* briquettes, briquettes produced with crushed and milled (C + M) and just milled (M) bark were compared (Table 3). There were effects of granulometry on the quality of the briquettes, except for durability.

It was possible to determine that most of the analyzed parameters were statistically higher in the conditions where the biomass bark was milled after the trituration process (C + M). Crushed and milled bark resulted in briquettes with higher apparent density ($1340\,kg\,m^{-3}$), energy density ($22.09 \times 10^6\,kJ\,m^{-3}$), and tensile strength by diametrical compression (4.7 MPa). The durability did not differ significantly between the two granulometry of the biomass and the volumetric expansion was higher in the only crushed bark briquettes (2.01%).

The difference in the apparent density found for the briquettes of the two bark conditions can be explained because smaller particles have larger contact surface (Quirino et al., 2012) and can be better accommodated during the densification process under pressure (Freitas et al., 2016). This promotes a greater apparent density in the briquettes with crushed and milled bark, resulting in higher energy density and RTDC of the briquettes with the crushed and milled bark, with $22.09 \times 10^6\,kJ\,m^{-3}$ and 4.7 MPa, respectively. As already discussed and indicated by several studies, there is a direct connection between these variables (Freitas et al., 2016; Sette et al., 2016; Castro et al., 2017).

Quirino et al. (2012) evaluating eucalyptus briquettes, formed from thin and thick particles, also found higher apparent and energy densities, as well as higher resistance to diametric compression for briquettes formed with smaller particles.

The durability did not differ between particle size, presenting 99.67% for the crushed and milled biomass and 99.70% for the crushed biomass only. Bergström et al. (2008) evaluated different particle sizes in pellet production; they also did not find any difference in the durability of their treatments, concluding that this parameter was not influenced by particle size.

The volumetric expansion was significantly lower in the crushed and milled biomass (1.56%) than in the crushed biomass (2.01%). The spaces between larger particles, previously occupied by air, are filled with smaller particles, causing greater cohesion between them and consequently a lower rate of expansion. Materials that have smaller particles have less expansion, allowing for better packing and more durability, as dense materials are usually less hygroscopic (Silva et al., 2015), as observed in this study.

To make sure that the chemical composition remained the same, the FTIR tests was performed. It was possible to identify that the chemical composition before and after the briquetting process did not change, Fig. 2.

In the absorbance signal of FTIR, the bands are formed from specific vibrations of the chemical bonds of the components, attributed to the symmetrical or asymmetrical vibrational stretches of the groups (Leão et al., 2017). It is possible to recognize the same peaks in several

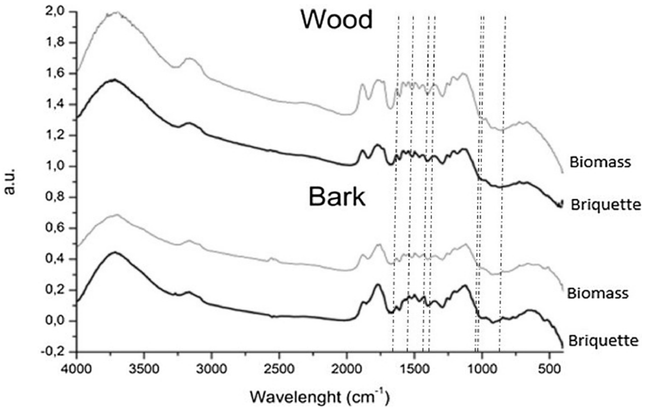

Fig. 2. Spectroscopic characterization of eucalyptus bark and wood, before and after briquetting.

vibrational bands (Fig. 2). The following structures were present: Lignin (wavenumber: around 858 and 1507 cm^{-1}), cellulose (around 1024, 1048, 1372 and 1317 cm^{-1}) and hemicellulose (around 1024, 1048, and 1737 cm^{-1}) (Ozgenc et al., 2018). This way, it was verified that the chemical composition before and after briquetting, remained the same, even after the pressure applied to the biomass.

4. Conclusion

The direct application of biomass of the *E. urograndis* bark, in a natural form, as a source of bioenergy presents disadvantages in relation to the wood due to the high ash content and low HHV.

- *E. urograndis* wood and bark biomass residues can be used as a source of raw material to produce high quality briquettes.
- It was possible to verify a gain of the energy density through the process of briquetting, when compared to the raw biomass, as well as an improvement on the physic-mechanical characteristics.

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