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Articles

Evaluation of kraft lignin and residues of sawmill for producing briquettes

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Abstract - The aim of becoming a society based on the rational utilization of the natural resources, has led to the consideration of many alternatives by academic and industrial sectors. The forest sector may be particularly prominent in trying to achieve these goals when using residues of their processes, for timber and pulp production. One of the most important requirements in society is the energy production. Co-products of wood processing and cellulose mills can be used for bioenergy generation. The densification of biomass involves handling, transportation and storage issues, and furthermore, when industrial forest residues such as lignin are added to this biomass, the final energetic product may have some improved properties, adding value to the chain. The purpose of this study was to evaluate the usage of the woody industrial waste, the sawdust from *Joannesia princeps* Vellozo enriched with Kraft lignin as an additive, aiming to produce briquettes. One of the main findings from this work was the possibility to obtain a briquette with better properties (higher bulk density and higher resistance) when using 6% of Kraft lignin as an additive and a pressure of 1500 PSI.

Avaliação de lignina kraft e resíduos de serraria para produção de briquetes

Resumo - O objetivo de se tornar uma sociedade baseada na utilização racional dos recursos naturais, tem levado à consideração de muitas alternativas pela academia e setor industrial. O setor florestal pode ter um destaque especial na tentativa de atingir esses objetivos ao utilizar resíduos de seus processos. Um dos requisitos mais importantes da sociedade é a produção de energia. Coprodutos do beneficiamento da madeira e das usinas de celulose podem ser utilizados no desenvolvimento da geração de bioenergia. A densificação da biomassa envolve questões de manuseio, transporte e armazenamento e, ainda, quando resíduos florestais industriais como a lignina são adicionados a essa biomassa, o produto energético final pode ter algumas propriedades melhoradas, agregando valor à cadeia produtiva. O objetivo deste estudo foi avaliar o aproveitamento do resíduo industrial lenhoso, a serragem de *Joannesia princeps* Vellozo enriquecida com lignina Kraft como aditivo, visando à produção de briquetes. Um dos principais resultados deste trabalho foi a possibilidade de se obter um briquete com melhores propriedades (maior densidade aparente e maior resistência) ao usar 6% de lignina Kraft como aditivo e pressão de 1500 PSI.

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Introduction

The use of all components from lignocellulosic biomass is related to integrated bio-refinery processes. This is a concept that has gained a lot of attention in the last decade and has resulted in the development of researches with the aim to advance and optimize the rational use of biomass for the generation of bio-energy, macro-molecules and aromatics (Luo & Abu-Omar, 2017). Lignocellulosic biomass as a renewable source has the potential to decrease the dependence of the society on fossil fuels to generate energy and mitigate the environmental problems, leading to a more sustainable society.

The main idea of the bio-refineries based on lignocellulosic biomass includes the separation of the main components of the biomass, such as carbohydrates and lignin, among others. Currently, there are industrial facilities in the world designed to extract and offer lignin to the market (Luo & Abu-Omar, 2017) related to the concept of bio-economy and sustainability (Macfarlane et al., 2014; Ndibewu & Tchieta, 2018).

The Kraft lignin (KL) may have different applications, however its use is still a challenge for having heterogeneous chemical compositions. It has been investigated for producing thermosets, thermoplastics and energy, for example (PNNL, 2007; Nielsen et al., 2009; Azadi et al., 2013; Duong et al., 2014; Scown et al., 2014; Upton & Kasko, 2016), and on this research the focus is on the agglutinating and energy properties.

Sawmills residues are a considerable natural resource, being inefficiently used raw material. According to Silva et al. (2021), the waste generated in the log process can achieve 40-60% (Obernberger & Thek, 2004) and generally is burned or discarded into landfills (Ackom et al., 2010). The main problem of selling these wastes to produce energy is their low density, which makes transportation expensive. However, there are many techniques for increasing the biomass density aiming to increase its usage to produce energy, e.g., pelleting and briquetting.

The densification process parameters, as temperature and pressure, and raw material properties directly influence in the properties and quality of the densified biomaterials (Clavijo et al., 2020). Richards (1990); Gilvari et al. (2019) and Silva et al. (2021) highlighted that parameters of abrasion and impact resistance, compressive strength, and density are important analyze quality characteristics of a densified biomaterial.

According to Gilvari et al. (2019), there are some examples of international standards to measure the quality of densified materials (for energy purposes) such as rupture strength (ISO17225-2, 2014; ÖNORM M 7135, 2000), bulk density (DIN 51705, 2001; DIN 15103, 2010); and heating values generated in the bio-material combustion (DIN 14918, 2010).

The lignin content is an important parameter in sawdust particles bonding (Shyamalee et al., 2015). Natural lignin in biomass cell wall allows the binding and softening in higher temperatures developing a compact unit (Kers et al., 2010; Lumadue et al., 2012; Ngusale et al., 2014). Therefore, the addition of technical lignin as a binder in the briquetting process can promote better bonding, size reduction, stability, durability and combustion efficiency properties (Wamukonya & Jenkins, 1995; Bhattacharya et al., 2002; Kers et al., 2010; Boschetti et al., 2019; Olugbade et al., 2019). The elemental composition of the biomass, bulk density, tensile strength and heating values are important parameters to characterize and study briquetting processes (Karunanithy et al., 2012; Maia et al., 2014; Jittabut, 2015; Sette Junior et al., 2017; Onukak et al., 2017; Deshannavar et al., 2018; Boschetti et al., 2019). In this context, the use of compacted biomass (i.e. briquettes) enriched with Kraft lignin may be a rational strategy alternative for using these forestry residues as renewable energy sources. It is possible to observe the rise in the number of studies that report the use of compacted biomass with high content of lignin to produce energy or the use of lignin as the binding material in densification processes (Boudet, 2000; Ekeberg et al., 2006; Lurii, 2008; Pereira et al., 2016; Gouvea et al., 2017; Leokaoke et al., 2018; Boschetti et al., 2019; Silva et al., 2021). Ayyachamy et al. (2013) affirm that lignin can also have non-fuel applications, related to polymer, resins, adhesives, carbon fibers development, and other bio-refinery uses.

The aforementioned studies are related to the most common raw materials found, such as *Pinus* and *Eucalyptus* woods. There are many other sources that require further investigations. For example, the species *Joannesia princeps* Vellozo, which is a pioneer species with a long lifespan, from the Brazilian Atlantic Forest. The species is studied for reforestation purposes, containing wood with some restrictions in use (Rolim & Piotto, 2019). According to the same authors this species presents long trunks, usually higher than 8 m, formed and straight with a slight devious and grows more than 0.75 cm year^{-1} at 1.30 m above ground level (DBH). These characteristics highlight the use of wood from this species as a rich source of raw material to be used in different wood segments. This wood feedstock has been used in sawmills, and the resulting residues can provide an opportunity to improve and enrich a green product that is economically viable and does not harm the environment. The production of densified materials that uses residues from wood processing industry and used wood as feedstock characterizes a densified material of class B (European Standard, 2009). The objective of this research was to evaluate the application of the woody industrial waste, the sawdust of *Joannesia princeps* Vell. enriched with Kraft lignin as an additive in different concentrations, aiming to produce and evaluate briquettes parameters for bio-energy generation.

Material and methods

Raw materials

In this work we used residues of *Joannesia princeps* Vell., from the preparation of wood timber. This wood species is considered a source of residues and is commonly found in the Atlantic Forest of some Brazilian states (Flora do Brasil, 2020).

Three trees samples were collected from an experimental station in the Vale Natural Reserve, located in Sooretama, Espírito Santo State, Brazil.

The residues were obtained from a machining process commonly found on a sawmill. The residues (sawdust), without bark, were collected and stored. The Kraft lignin used as an additive in the briquetting process was obtained from a Brazilian kraft pulp mill company that processes *Eucalyptus* spp. as feedstock and it was used without any modification.

Raw materials characterization

The chemical composition of the wood was determined by grounding 1 kg of wood residue in a Wiley type mill to produce sawdust of variable sizes. The obtained sawdust was screened according to the Tappi Standard T 257-cm12 (Tappi, 2012). The sawdust fraction that passed through the 40 mesh, and was retained in the 60 mesh screen was air dried and conditioned in a room with controlled temperature and humidity (20 ± 1 ˚C, 50 ± 2%, respectively) until an equilibrium moisture was achieved (~10%). This sawdust (raw sawdust) was used for chemical analyses. The analysis of ash was carried out directly on the raw sawdust, according to the Tappi Standard T 15 os-58 (1991) combined with T 211 (Tappi, 2002). The extractive contents of the biomass were assessed by extractions using ethanol/toluene (1:2); ethanol and hot water solvent, according to the Tappi Standard T264 cm-97 (1997). The syringyl:guaiacyl ratio was determined following the alkaline nitrobenzene oxidation proposed by Lin & Dence (1992). This method describes the degradation of the constitutive lignin building units - p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S) moieties into aldehydes.

The contents of uronic acids, acetyl groups and sugars (glucan, mannan, galactan, xylan and arabinan) in the extractive free biomass were determined (Scott, 1979; Solar et al., 1987; Wallis et al., 1996; SCAN, 2009). The uronic acid was measured by colorimetric determination, acetyl groups were determined by the liberated acetic acid by high performance liquid chromatography (HPLC), and the sugar content was determined in an acid hydrolyzate by ion chromatography (IC). The acid insoluble and the soluble lignin were determined according to TAPPI T222 om-97 (1998) standard procedure and TAPPI UM 250 (1991), respectively.

The Deutsches Institut Für Normung method (DIN) EN 14918 (2010) was used to determine the low and high heating values (LHV and HHV, respectively) using an IKA300® adiabatic calorimeter pump. The LHV and HHV were determined by equations available in Annex E in the DIN EN 14918 (2010). The elementary analysis of the wood biomass followed the DIN EN 15104 (2011) procedures. This method consists in the combustion of a known mass of the sample in oxygen converted into ash and gaseous products, and the carbon dioxide, water vapour and nitrogen mass fractions of the gas stream are determined quantitatively by instrumental gas analysis procedure.

Briquetting

The briquetting process followed Silva et al. (2021) method. The experiment was conducted in a Lippel B-32 piston press machine. The process temperature (120 °C), pressing and cooling times (6 min) were preliminary tested in function of the lignin plasticization, and three compression pressure conditions were analyzed: 900 pounds per square inch (PSI); 1,200 PSI; and 1,500 PSI.

In order to avoid problems with the briquetting machine due to lignin plasticization, the proportion of kraft lignin mixed with the wood fines was 0, 2, 4, and 6%. The mass of each briquette had 20 g. The experiTment was divided into 12 treatments, with 6 repetitions each one.

After the briquetting process, visual analyses were performed followed by measurements of height and diameter evaluating the presence of cracks and deformations.

Evaluation of briquettes performance

These studied variables include moisture content, heating value, abrasion resistance, particle density, ash content, and ash melting point. The bulk density analysis was performed according to Vital (1984). The modulus of rupture value, conducted by the compressive strength test, was calculated as a function of the area and the resistance strength of the briquette to the rupture stress.

The analysis of the modulus of rupture and heating values followed the methodology described by Silva et al. (2021). The modulus of rupture was performed in an universal machine in accordance to Brazilian standard NBR ISO 11093-9 (ABNT, 2009), and the heating values were determined following the DIN 14918 (2010) standard.

The normality and analyses of variance in the briquettes data followed Shapiro & Wilk (1965) and Cochran test (1950), respectively. When significant differences were found we used the Tukey's test at 95% significance level.

Results

Characterization of the raw material

The results on the composition of the species (lignin, syringyl:guaiacyl ratio, acetyl groups, uronic acids, carbohydrates content, percentage of extractives, and ash contents) are described in the Table 1, taking into account the importance of the chemical composition of the materials related to the bulk density and briquette rupture modulus. Table 2 and 3 presents the elemental compostion and heating values of the wood residues from *Joannesia princeps* biomass, and kraft lignin, respectively.

Analyzing the Table 1, it is possible to highlight the low content of lignin, S/G ratio, acetyl groups and uronic acids. The data also emphasizes the high content of extractives and ash present in the composition of the *Joannesia princeps* biomass.

The elemental composition of *Joannesia princeps* Vell. presented in Table 2 showed low content of nitrogen and a high content of sulphur. The biomass presented average heating values (LHV and HHV).

The composition of the kraft lignin (KL) (Table 3) showed significant content of ash, and average heating values (LHV and HHV).

Table 1. Chemical composition of residues from *Joannesia princeps*, Espírito Santo State, Brazil.

Lignin (%)			Carbohydrates (%)							Total extractives (%)	Ash (%)	S/G	Sum (%)
AIL	ASL	Total	Acetyl groups	Uronic acids	Glc	Xyl	Man	Ara	Gal				
18.9	2.6	21.5	2.2	2.8	44.4	12.1	1.8	0.6	0.7	11.2	2.5	1.52	97.3

AIL: acid insoluble lignin; ASL: acid soluble lignin; Glc: glucan; Xyl: xylan; Man: mannan; Ara: arabinan; Gal: galactan; S/G: syringyl:guaiacyl ratio.

Table 2. Elemental analysis and low heating value (LHV) and high heating value (HHV) of the wood residues from *Joannesia princeps*, Espírito Santo State, Brazil.

Elemental Analysis (%)						LHV (MJ Kg^{-1})	HHV (MJ Kg^{-1})
C	H	N	S	O	Sum		
48.0	5.72	0.11	0.08	43.6	97.5	17.3	18.5

C: carbon; H: hydrogen; N: nitrogen; S: Sulphur; O: oxygen; LHV: low heating value; HHV: high heating value.

Table 3. Compositional data and heating values of the lignin from *Eucalyptus* spp. Brazilian kraft pulp mill company.

Carbohydrates (%)					Ash (%)	LHV	HHV ($MJ\ Kg^{-1}$)
Glucan	**Xylan**	**Mannan**	**Arabinan**	**Galactan**		**($MJ\ Kg^{-1}$)**	
0.13	0.09	0.36	0.03	0.05	14.2	20.8	21.7

LHV: low heating value; HHV: high heating value.

Briquetting process

The results related to the briquetting processes on the bulk density, modulus of rupture (MOR) and heating values are presented in Table 4. These results are considered important parameters for the quality of the briquettes. It is important to highlight that no significant variations were observed in the sizes (height and diameter) of the studied briquettes.

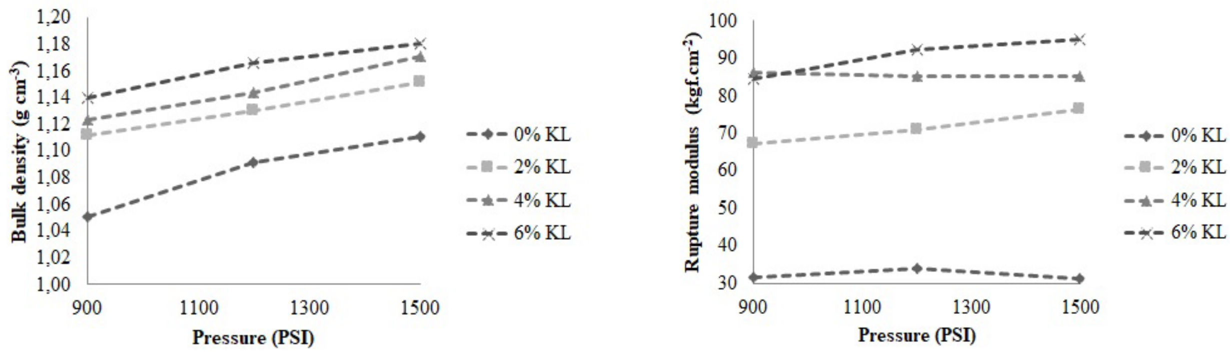
The incorporation of 2% of KL promotes a significant increase in the mechanical characteristics doubling the tensile properties of the material, but did not have significant implications in the bulk density and the heating values. In general, the inclusion of 6% of KL contributed to the increase in the bulk density and it increased the rupture modulus of the briquettes. The bulk density variables presented greater differences when the pressure of 900 PSI was applied. Whereas, the rupture modulus presented greater differences at a pressure of 1,500 PSI (Figure 1).

Concerning the briquettes heating values (LHV and HHV), it was possible to observe that the briquette made with 6% KL and 1,500 PSI presented the highest heating value, but these values were not statistically different among studied treatments. Based on the observed data, the lignin addition did not impair the briquettes heating values.

Table 4. Mean values of bulk density modulus of rupture (MOR), and heating values of *Joannesia princeps* mixed with kraft lignin briquettes.

Treatments	Pressure (PSI)	Kraft lignin (%)	($g\ cm^{-3}$)	MOR ($kgf\ cm^{-2}$)	LHV ($MJ\ kg^{-1}$)	HHV ($MJ\ kg^{-1}$)
T1	900	0	1.05 ± 0.01 ^{f}	31.49 ± 1.47 ^{de}	17.6 ± 0.1 ^{ab}	19.4 ± 0.10 ^{abc}
T2	1,200	0	1.09 ± 0.02 ^{de}	34.07 ± 2.33 ^{d}	17.4 ± 0.1 ^{cd}	19.2 ± 0.10 ^{cd}
T3	1,500	0	1.11 ± 0.01 ^{d}	26.14 ± 6.15 ^{de}	17.5± 0.0 ^{c}	19.3 ± 0.00 ^{c}
A1	900	2	1.11 ± 0.03 ^{d}	63.02 ± 10.9 ^{c}	17.7 ± 0.0 ^{a}	19.5 ± 0.00 ^{a}
A2	1,200	2	1.13 ± 0.02 ^{cd}	66.98 ± 12.33 ^{c}	17.7 ± 0.1 ^{a}	19.5 ± 0.05 ^{ab}
A3	1,500	2	1.15 ± 0.01 ^{bd}	73.90 ± 6.33 ^{c}	17.6 ± 0.0 ^{b}	19.4 ± 0.00 ^{ab}
B1	900	4	1.12 ± 0.03 ^{cd}	86.21 ± 12.4 ^{a}	17.6 ± 0.0 ^{b}	19.4 ± 0.05 ^{ab}
B2	1,200	4	1.14 ± 0.02 ^{bcd}	85.32 ± 2.59 ^{b}	17.3 ± 0.1 ^{d}	19.1 ± 0.05 ^{de}
B3	1,500	4	1.17 ± 0.01 ^{a}	85.12 ± 6.85 ^{b}	17.2 ± 0.0 ^{e}	19.0 ± 0.00 ^{e}
C1	900	6	1.14 ± 0.01 ^{cd}	84.46 ± 6.26 ^{b}	17.5 ± 0.0 ^{c}	19.3 ± 0.00 ^{c}
C2	1,200	6	1.17 ± 0.01 ^{a}	92.30 ± 5.81 ^{a}	17.6 ± 0.0 ^{b}	19.4 ± 0.00 ^{ab}
C3	1,500	6	1.18 ± 0.01 ^{a}	95.17 ± 7.45 ^{a}	17.7 ± 0.1 ^{a}	19.5 ± 0.10 ^{ab}

LHV: low heating value; HHV: high heating value. Averages followed by the same letter in the column do not differ statistically by Tukey test ($p \geq 0.05$).



(A) (B)

Figure 1. Properties of the briquettes produced with *Joannesia princeps* and kraft lignin, being: (A) bulk density; (B) rupture modulus. KL = kraft lignin, mixed with the wood fines at 0, 2, 4 and 6%.

Discussion

Characterization of the raw material

There is a lack of literature regarding the chemical composition of Brazilian native hardwood species, therefore the comparison of the data from this study were compared to *Eucalyptus* spp., which is the most abundant hardwood species used in Brazil for energy application.

The evaluated biomass of *Joannesia princeps* presented a lower content of lignin (Table 1, AIL: 18.9%; ASL: 2.6%), when compared to other wood species, such as *Eucalyptus* spp. (AIL: 21.0 - 30.2%; ASL: 2.9 - 5.1%) studied previously (Gomide et al., 2005; Neves et al., 2011; Trugilho et al., 2012; Zanuncio et al., 2013; Pereira et al., 2013; Eichler et al., 2017), which are also used for producing briquettes (Boschetti et al., 2019). Lignin content is related to the energy efficiency (Marsk, 2008; Mendu et al., 2012) of the lignocellulosic biomass, which is essential for the adhesive properties of the material. Lignin can improve adhesion between particles, resulting in better bonding and stability (Li et al., 2018). This is possible because of the condensation reactions of the lignin during the pressing process contributing to the bonding mechanism (Okuda et al., 2006).

The syringyl:guaiacyl (S/G) ratio of *J. princeps* was lower (1.52), when compared to the eucalyptus ratio, values range from 2.0 to 3.8 (Gomide et al., 2005; Mokfienski et al., 2008; Pereira et al., 2013; Martino et al., 2013; Morais et al., 2017). The heating value of wood can also be influenced by the S/G ratio (Protásio et al., 2017). This information is important to verify that the biomass lignin is more reactive due to the higher content of coniferyl groups compared to eucalyptus. The guaiacyl unit has a higher C/O ratio compared to the syringyl unit and this increases the heating values (Soares et al., 2014; Protásio et al., 2017).

Regarding the carbohydrate content, as expected for hardwoods, the main sugars were the glucan (44.4%) and xylan (12.1%), similar to the results found in the study of Gomide et al. (2005); Mokfienski et al. (2008); Neves et al. (2011) and Morais et al. (2017) that presented glucan (Glc) values varying from 38.0 to 51.0% and xylan (Xyl) composition values ranging from 9.9 to 14.7%, using *Eucalyptus* spp. in Brazil.

The amount of acetyl groups and uronic acids, both hemicelluloses components (Morais et al., 2017) can determine the potential use of the wood. The presence of acetyl groups can influence the digestibility of the biomass being a limit factor for conversion processes (Pan et al., 2006; Melati et al., 2019). The acetyl groups reported in this study (2.2%) is lower than those found in hardwood species such as *Eucalyptus* spp. (1.6 - 3.6%) (Gomide et al., 2005; Morais et al., 2017).

The content of uronic acid (2.8%) was lower than reported by the literature studying *Eucalyptus* spp. (3.2 - 5.9%) (Gomide et al., 2005; Zanuncio & Colodette, 2011; Carvalho et al., 2015; Morais et al., 2017). These acids content suggest that the wood of *J. princeps* can be used for the bleached pulp production, and reinforce the medicinal use (Donato-Trancoso et al., 2014), as it has potential in the development of chemicals for pharmaceutical, medicinal and materials industries (Tomaszewska et al., 2018).

According to Gomes et al. (2015), hardwood species (i.e. *Eucalyptus* clones) present extractives up to 10%, depending on the extraction method and solvents used. The presence of high levels of substances such as extractives favours generation and release of high levels of energy (Zanuncio et al., 2013).

Another important parameter of the biomass for energy application is the ash content. The ash can influence negatively the thermal process and the used equipment (Brand, 2010; Paula et al., 2011a, 2011b; Protásio et al., 2011a, 2011b; Silva et al., 2021). The ash contents of several species, including *Eucalyptus* may vary between 0.10 and 0.83%, as observed by Ferreira et al. (1997); Neves et al. (2011); Protásio et al. (2011b); Pereira et al. (2013); Trugilho et al. (2015); Eichler et al. (2017); Morais et al. (2017) and Simetti et al. (2018), while for *Pinus* species values between 0.15 and 0.25% were reported (Mendes et al., 2002).

The elemental composition of the wood biomass of the evaluated raw material (Table 2, C: 48.0%; H: 5.72%; N: 0.11%; S: 0.08%; O: 43.6%) was similar to those for *Eucalyptus* wood (Trugilho et al., 2012; Pereira et al., 2013; Eichler et al., 2017; Silva et al., 2019), except for N (0.2 - 2.4%), which presented a much lower level than that found for *Eucalyptus* clones (Eichler et al., 2017). The S content (0.08%) was higher than that observed in *Eucalyptus* wood (0.01 - 0.09%), however it has been studied that the briquetting process can reduce S release during combustion (Han et al., 2019).

The low and high heating values (LHV and HHV, respectively) of *J. princeps* wood were quite similar to those found in the literature (Turns, 2013; Eichler et al., 2017; Pereira et al., 2016; Boschetti et al., 2019) for *Eucalyptus* and *Pinus* biomass. Elemental analysis and biomass properties are intrinsically related to heating values (LHV and HHV), since H is the element that releases the highest amount of energy during combustion, followed by C (Turns, 2013; Boschetti et al., 2019).

Regarding the technical lignin composition (Table 3) it was possible to observe that the ash content in the studied kraft lignin (14.2%) was much higher than the values reported in the literature (Tomani, 2010; Teixeira et al., 2018; Boschetti et al., 2019), but similar to that found by Pereira et al. (2016).

Briquetting Process

It is important to mention that according to the European Standards (2009) that approaches the pellets specifications, there is a limit of additive that can be incorporated in the densified material. This limit is 2% of the pressing mass of the material, and this percentage is related to the market price of the final densified briquette.

The kraft lignin (KL) should be added to the briquettes to increase the resistance when using lignocellulosic materials at compaction temperatures below the ideal levels for plasticization, contributing to the increment in the heating value (Gouvêa et al., 2017).

The temperature in briquetting process has significant impact on the briquette quality and strength (Kers et al., 2010). The lignin softening temperature is correlated to the moisture content of the feedstock, being around 130 °C in 10% (wet basis) moisture (Shyamalee et al., 2015). The glass transition temperature (Tg) is an important factor to produce durable and stable bonding briquettes (Kaliyan & Morey, 2010). This parameter is related to the viscosity and mobility of the binding components (Finney et al., 2009; Modiri et al., 2016; Leokaoke et al., 2018).

However, the lignin origin interferes in its properties, being hardwood lignin Tg (124 - 174 °C) and softening temperature lower when compared with softwoods lignin, due to the fewer presence of phenolic hydroxyl groups (Glasser, 1999; Kubo & Kadla, 2004; Stelte et al., 2012; Kun & Pukánszky, 2017).

The working humidity higher than 8% would cause the briquettes to rupture according to Kaliyan & Morey (2009). The feedstock moisture can impair the densification process and produce a lower durability briquette (Quirino, 1991; Moreno et al., 2016; Silva et al., 2021).

The amount of lignin per kg of dry matter is important in briquetting (Mankowski & Kolodziej, 2008; Kers et al., 2010; Alaru et al., 2011). According to Boschetti et al. (2019), higher concentrations of KL can promote significant modifications in briquettes properties, and lower concentrations can also contribute to resistance and calorific variables.

Berghel et al. (2013) studied sawdust compactation with KL to develop pellets and concluded that from 1% of added KL there are modifications in mechanical durability. Another important factor is the purity of the lignin used in the densification processes, since despite having similar properties, the technical lignin commonly have different structure and compositions related to the manufacturing process (Vishtal & Kraslawski, 2011).

As expected, the bulk density increased, due to the agglutination and plasticization of lignin. The briquettes incorporated with 6% of KL showed greater LHV and HHV difference when compared to the ones produced by the main standard procedures, which presented the best results. The greatest difference was found in the control treatment at 900 PSI compared to the treatment that incorporated 6% of KL to 900 PSI (difference of 0.09 g cm^{-3}). According to Silva et al. (2021), briquettes with higher density and strength, can provide higher energy content (Onukak et al., 2017) and burn for an extended time (Obernberger & Thek, 2004). The heating values of *J. princeps* sawdust briquettes did not show difference between the studied treatments and presented lower values when compared to literature data. Boschetti et al. (2019), using the same process temperature and similar pressure conditions for *Eucalyptus* and *Pinus* biomass, achieved higher values of LHV, ranging from18.5 to 18.8 KJ kg^{-1}. This can be explained by the distinct chemical composition of the studied biomass and the KL. The use of other technical lignin and lignocellulosic biomass is recommended for a better understanding of agglutination process interference in different raw material sources of densification.

The rupture modulus increased after a rise in pressure (1,500 PSI) and a larger amount of lignin was incorporated (6% KL). The maximum rupture significantly interferes with the quality of briquettes, since it is related to its transport and storage and to a certain extent to its durability (Gouvêa et al., 2017). The higher the density, the higher the compressive strength modulus (Onukak et al., 2017).

Results with briquettes of *Hymenolobium petraeum* Ducke, *Eucalyptus* spp., *Pinus* spp., and *Astronium concinnum* (Engl.) Schott proved that 6% of impregnated KL gives better physical and mechanical properties (Boschetti et al., 2019; Silva et al., 2021).

Conclusions

The addition of kraft lignin (KL) to *Joannesia princeps* sawdust briquettes contributes to the improvement of physical and mechanical properties, regarding to density, mechanical durability, and strength. The addition of KL for densified biomaterials production is feasible, as long as purer lignin is used. It was possible to obtain a briquette with better properties (higher bulk density, and higher tensile strength to compression) when using 6% of KL as an additive and a pressure of 1,500 PSI. However, the studied treatments did not imply in heating values modifications. Considering the market aspects of the briquettes, an inclusion of 2% KL can promote significant modifications in the mechanical properties allowing the production of more resistant and durable bio-materials. In line with the sustainable uses of the available biomass, the use of a briquette produced under these conditions provides the potential use of the lignocellulosic residues generated by a sawmill as raw material/feedstock for sustainable energy generation. In addition, using a common residue from the pulp mills adds technological value to the final product, enabling the generation of energy and the maximization of the profit generated in this process.

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