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Properties of raw materials and pellets produced with blends of reforestation woods

Propriedades da matéria-prima e de pellets produzidos com misturas de madeiras de reflorestamento

Propiedades de materias primas y pellets producidos con mezclas de madera de reforestación

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Abstract

A large amount of biomass is available in Brazil, which may give an alternative for pellet production. With the market constantly growing, the search for raw materials with the potential for energy generation has become a necessity in serving sector demands. *Eucalyptus* sp. and *Pinus* sp. are the main sources of timber in Brazil. Therefore, the main objective of this study was to evaluate the quality of pellets produced with different blend proportions of *Eucalyptus* sp. and *Pinus* sp. wood particles from reforestation. The percentages of eucalyptus in relation to pine were 0, 10, 20, 50, 80 and 90%. Biomass characterization was performed. The pellets were produced in a lab-scale horizontal pelletizing matrix with a heated steam system. The pellets were evaluated for their physical, chemical, energetic and mechanical properties. The higher heating value decreased with an increasing percentage of *Eucalyptus* sp. in the blend. The chlorine and ash contents were within the range established by the international parameters for wood pellets. The mean mechanical durability of the produced pellets was 93%. Pellets with 80% eucalyptus and 20% pine stood out for their density, compaction rate and mechanical properties.

Keywords: Bioenergy; Biomass densification; Forest residue; Solid biofuel.

Resumo

No Brasil, tem-se disponível grande quantidade de biomassas que podem ser alternativas para produção de pellets, e com o mercado em constante ascensão, a busca por matérias-primas com potencial para geração de energia torna-se uma necessidade em atendimento ao setor. *Eucalyptus* sp. e *Pinus* sp., são as principais fontes de fornecimento de madeira no Brasil. Portanto, o objetivo principal deste estudo foi avaliar a qualidade de pellets produzidos com diferentes proporções de misturas entre partículas de madeiras de reflorestamento, *Eucalyptus* sp. e *Pinus* sp. As porcentagens de eucalipto em relação ao pinus foram: 0, 10, 20, 50, 80 e 90%. Foi realizada a caracterização das biomassas. Os pellets foram produzidos em matriz peletizadora horizontal de escala laboratorial com sistema de vapor aquecido. Os pellets foram avaliados quanto às propriedades físicas, químicas, energéticas e mecânicas. O poder calorífico superior diminuiu com o aumento da porcentagem de *Eucalyptus* sp. na mistura. Os teores de cloro e cinzas estão dentro da faixa estabelecida pelos parâmetros internacionais para pellets de madeira. A durabilidade mecânica média dos pellets produzidos foi de 93%. Os pellets com 80% de eucalipto e 20% de pinus destacaram-se quanto à densidade, taxa de compactação e propriedades mecânicas.

Palavras-chave: Bioenergia; Biocombustível sólido; Resíduo florestal; Densificação da biomassa.

Resumen
En Brasil, hay una gran cantidad de biomasa disponible que puede ser alternativa para la producción de pellets, y con el mercado en constante crecimiento, la búsqueda de materias primas con potencial para la generación de energía se convierte en una necesidad para atender al sector. Eucalipto sp. y *Pinus* sp., son las principales fuentes de abastecimiento de madera en Brasil. Por lo tanto, el objetivo principal de este estudio fue evaluar la calidad de los pellets producidos con diferentes proporciones de mezclas entre partículas de madera de reforestación, *Eucalyptus* sp. y *Pinus* sp. Los porcentajes de eucalipto con relación al pino fueron: 0, 10, 20, 50, 80 y 90%. Se realizó la caracterización de las biomasas. Los gránulos se produjeron en una matriz de granulación horizontal a escala de laboratorio con un sistema de vapor calentado. Los pellets fueron evaluados en cuanto a propiedades físicas, químicas, energéticas y mecánicas. El poder calorífico superior disminuyó con el aumento del porcentaje de *Eucalyptus* sp. en la mezcla. Los contenidos de cloro y cenizas se encuentran dentro del rango establecido por las normas internacionales para pellets de madera. La durabilidad mecánica media de los gránulos producidos fue del 93%. Los pellets con 80% de eucalipto y 20% de pino se destacaron en cuanto a densidad, velocidad de compactación y propiedades mecánicas.
Palabras clave: Bioenergía; Biocombustible sólido; Residuos forestales; Densificación de biomasa.

1. Introduction

Bioenergy plays an important role in the deceleration of global warming processes. The uses of renewable energy sources to replace fossil fuels, as well as carbon capture and storage, are among the main mitigation options for achieving climate goals (Birdsey et al., 2018).

Much has been written on environmental issues related to the increasing use of woody biomass for bioenergy (Birdsey et al., 2018; Schlesinger, 2018). However, biomasses obtained from different sources have certain characteristics, such as the shapes and sizes of heterogeneous particles, a high humidity and a low energy density, making their use as solid biofuels more difficult (Castellano et al., 2015).

One of the possibilities for reducing or eliminating the main problems associated with the direct use of biomass is through compaction processes, such as pelletizing (Sette et al., 2016).

This technology improves the physical properties of the biomass and produces a more uniform, stable and more energy-intensive product to produce environmentally friendly fuels (Whittaker & Shield, 2017) and consequently solves the problems of transport, storage and handling of low-density materials, as reported by Ríos-Badrán et al. (2020).

The raw materials currently used for the production of solid biofuels are mainly wood waste, such as trimmings and sawdust (Hansted et al., 2016).

Eucalyptus wood pellets produced in Brazil are a promising option because eucalyptus is the most important forest species for the wood supply in the country (Eufrade et al., 2016). These wood pellets are similar to pine pellets, which are the main raw materials used worldwide for the production of this biofuel (Monedero et al. 2015).

Thus, the objective of this study was to evaluate pellets produced with different proportions of *Eucalyptus* sp. and *Pinus* sp. and to determine the blend that results in pellets with characteristics more favorable toward domestic and industrial use.

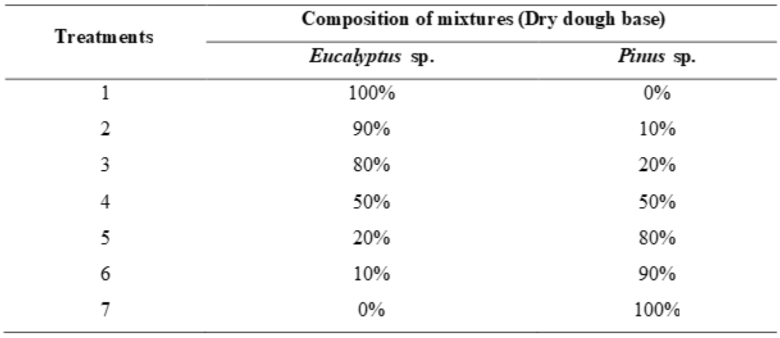
2. Methodology

2.1 Collection and preparation of the raw material: *Eucalyptus* sp. (E) and *Pinus* sp. (P)

The raw material used for the execution of this work was provided by a pellet sector company located in Ressaquinha - Minas Gerais, Brazil. The raw material consists of *Eucalyptus* sp. and *Pinus* sp., with dimensions close to 5 mm. The particles of *Eucalyptus* sp. are derived from the mechanical processing of the commercial eucalyptus species found in the region of the company and were obtained from hulled wood. The *Pinus* sp. particles are from sawmill waste, which is also located in the region.

After the raw material was collected, 7 (seven) treatments were prepared, as described in Table 1. Subsequently, the moisture of the treatments was adjusted to 16 ± 2%, on a dry basis.

Table 1. Composition of treatments.



Treatments	Composition of mixtures (Dry dough base)	
	Eucalyptus sp.	*Pinus* sp.
1	100%	0%
2	90%	10%
3	80%	20%
4	50%	50%
5	20%	80%
6	10%	90%
7	0%	100%

Source: Authors.

2.2 Characterization of the raw material

The proportions of *Eucalyptus* sp. and *Pinus* sp., i.e., the 7 (seven) treatments, were assessed for the following characteristics:

The moisture, on a dry basis, was determined according to the DIN EN 14774-1 standards (Deutsches Institut Für Normung - DIN, 2010).

The determination of the bulk density of the treatments was performed using a 100 cm³ graduated cylinder filled with the sample. The filled cylinder was weighed on a scale with a precision of 0.1 g. The bulk density was calculated using the ratio between the obtained mass and the sample volume (100 cm³).

The extractive contents were determined according to the TAPPI 204 cm-97 standard (Technical Association of the Pulp and Paper Industry - TAPPI, 1997). The total lignin was determined following the procedures of the TAPPI T 222 om-02 standard (Technical Association of the Pulp and Paper Industry - TAPPI, 2002).

Holocellulose was obtained by the difference, according to Equation 1.

$$HOL = 100 - EXT - TL - AS \qquad (1)$$

In which:

- HOL: Holocellulose (%);
- TL: Total lignin (%);
- AS: Ash (%).

The immediate chemical characterization used to quantify the volatile materials, such as ash and, by difference, fixed carbon, was obtained according to the description of the ASTM D1762-84 standard (American Society for Testing Materials - ASTM, 2007).

Quantification of the chloride (Cl-) for the *Eucalyptus* sp. and *Pinus* sp. samples was performed by the decomposition of the samples via microwave-initiated combustion (Multiwave 3000®, Microwave Sample Preparation System). Chlorine determination was performed using an ion chromatograph (Professional 850, Metrohm, Switzerland), equipped with a conductivity detector.

The determination of the higher heating value (HHV) was performed using an IKA C-200 digital calorimeter according to the procedures described in ASTM E711-87 (American Society for Testing Materials ASTM, 2004).

2.3 Pelletizing process

Approximately 3 (three) kg of pellets were produced per treatment (Table 1), except for Treatment 1. The limitation of the pelletizer prevented the production of 100% eucalyptus pellets.

The densification process of the treatments was performed in a laboratory pellet press (Amandus Kahl) model 14-175 with a capacity of 30 kg h-1 and a horizontal flat matrix with 6 mm diameter channels.

The mean pelletizing temperature was approximately 105 °C, and the rotational speed of the rollers was 1,500 rpm. A pellet feed system consisting of an electric motor, a speed controller and an endless screw with steam injection produced by an autoclave was used. The injected vapor was at a pressure between 0.5 and 1 kgf cm-².

After production, the pellets were cooled to room temperature and conditioned in plastic bags until testing.

2.4 Characterization of the pellets

2.4.1 Physical properties

Determination of the moisture, on a dry basis, and the bulk density of the pellets was performed according to the same methodologies used for the characterization of the raw materials.

The unit bulk density of the pellets was determined using the stereometric method, i.e., the volume was calculated considering the cylindrical shape of the pellets, and the mass was obtained with the use of a precision scale of 0.01 g. A measurement of 100 pellets per composition was performed, similar to the procedure adopted by Silva et al. (2020).

The compaction rate was obtained by the ratio between the bulk density of the pellets and the bulk density of the biomass or the blend between them.

2.4.2 Chemical properties

The pelleting process does not alter the chemical properties of the raw materials (Maraver et al., 2015). Therefore, for the chemical characterization of the pellets, the same values found for the treatments before the pelleting process were considered.

2.4.3 Energy properties

The higher heating value (HHV) used to calculate the energy properties was the same as that obtained for the treatments before pelletizing. This similarity is as Sette et al., (2018) verified, who worked with the densification of the hybrid *Eucalyptus grandis* x *Eucalyptus urophylla* by means of briquetting and concluded that the HHV values before and after the process are not different.

Thus, the unit energy density of the pellets, the product of the unit density of the pellets and the mean higher heating value (HHV) were calculated.

The bulk energy density of the pellets was obtained by the product of the bulk densities (bD) and the mean higher heating value (HHV).

2.4.4 Mechanical properties

The mechanical durability and the percentage of fine particles (particles smaller than 3.15 mm) were determined using the Ligno-Tester equipment, Holmen®, according to the DIN EN 15210-1 standard (Deutsches Institut Fur Normung - DIN, 2010b).

The hardness or resistance to manual compression, in kg, was determined using a manual durometer with an Amandus Kahl scale of 0 to 100 kg. One pellet was added to the hardness tester at a time with an increasing load until the sample fractured. Then, the maximum load that a pellet could withstand before breaking was registered. Twenty-five pellets were considered for each treatment.

2.5 Statistical analysis of the data

The experiment was conducted according to a completely randomized design (CRD) with seven treatments for the biomass characterization and six treatments for evaluating the pellets produced with the blend between them.

The results were subjected to an analysis of variance (ANOVA), using the F test at a 5% significance level to verify the differences between the treatments. A regression analysis was performed with significant differences between the treatments.

The appropriate model was adjusted by considering the coefficient of determination (R^2), the residual standard error and the residual distribution when significant differences between treatments were established.

All statistical analyses were performed using R software, version R version 3.5.1. (R Foundation for Statistical Computing, 2018).

3. Results and Discussion

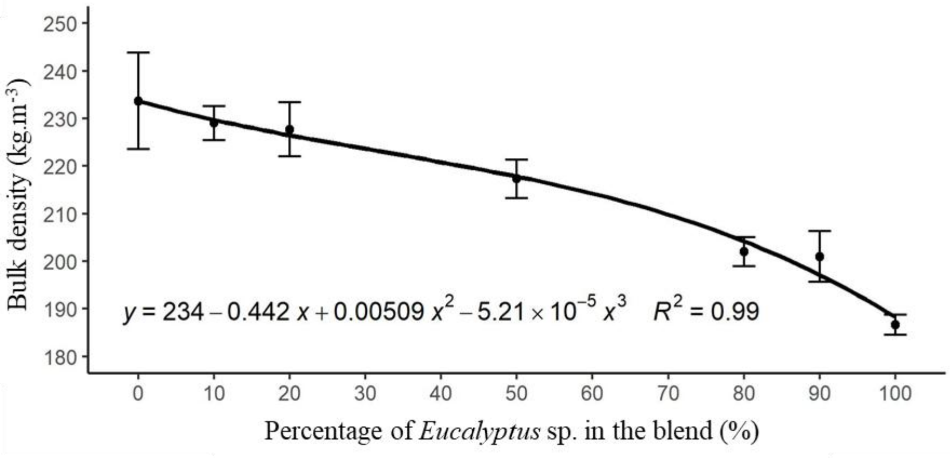
3.1 Characterization of biomasses

On a dry basis, the moisture of the analyzed treatments after conditioning was 16 ± 2%. It is known that the biomass moisture is an important factor because it affects the pellet quality (Samuelsson et al. 2012). Water also plays a significant role in the pelletizing process and may act as a bonding agent that affects the mechanical durability. In addition to being negatively correlated with friction during pelletizing, it functions as a lubricant, which lowers the friction in the pelletization matrix (Kaliyan & Morey, 2009).

Studies have indicated that the biomass moisture for the production of pellets is between 5 and 12% (Li & Liu, 2000; Obernberger & Thek, 2010), showing that ideal moisture varies for different types of raw material and production configurations, possibly due to the chemical composition of the material and particle size.

The bulk density of the treatments (Figure 1) varied between 186.66 and 229.00 kg m-3. According to Tumuluru et al. (2011), the bulk density of sawdust ranges from 150 to 250 kg m-3. Thus, all the values obtained are consistent with the values found by Tumuluru et al. (2011).

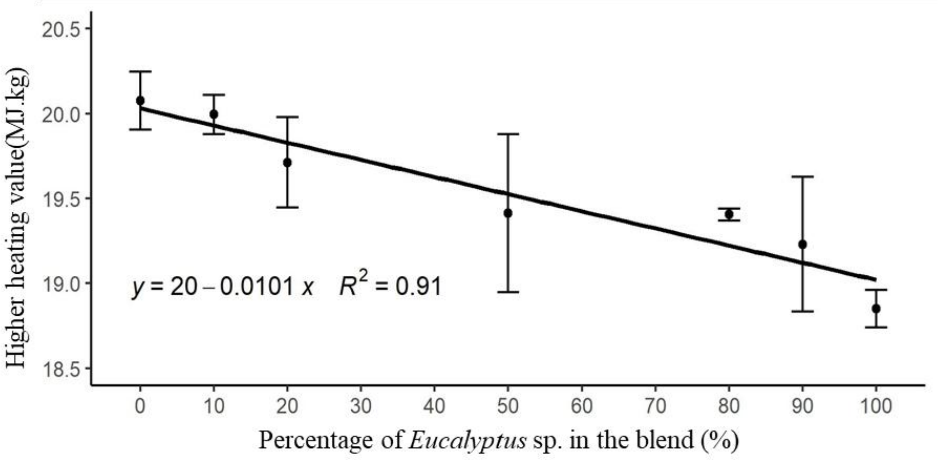
Figure 1. Functional relationship observed between bulk density and percentage of *Eucalyptus* sp. in the blend.



Source: Authors.

The higher heating value (HHV) expresses the amount of energy contained in a mass of completely dry wood. This value consists of one of the most important properties to characterize a material as fuel (Gillespie et al., 2013). In this respect, different percentages of eucalyptus were observed in the biomass blend (Figure 2). In general, treatments with higher pine proportions showed higher HHV values, possibly due to the chemical nature of the extractives present in this biomass, as well as the quantity and type of lignin (Van Loo and Koppejan, 2009). The highest mean value was 20.08 MJ · kg-1 (100% pine), and the lowest was 18.85 MJ · kg-1 (100% eucalyptus).

Figure 2. Functional relationship observed between higher heating value (HHV) and percentage of *Eucalyptus* sp. in the blend.



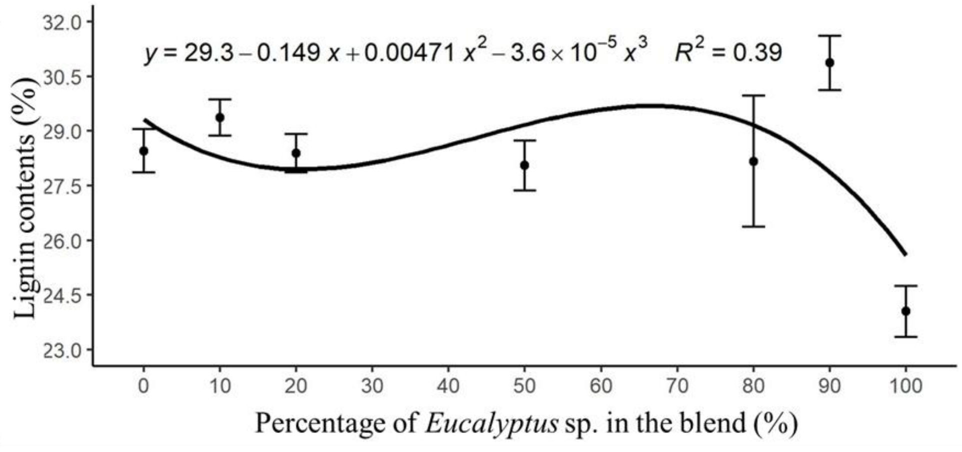
Source: Authors.

Similar HHV ranges have been reported for several species of wood and energy crops in the literature (Telmo & Lousada, 2011; Carroll & Finnan, 2012; Acda, 2015).

Lignin, extractives and ash contents are fundamental for the selection of lignocellulosic materials for energy production because they directly influence the heating value of the materials either positively or negatively (Paula et al., 2011; Demirbas, 2001).

Figure 3 shows that the percentage of eucalyptus in the blend had an effect. According to the fitted curve, the lignin content decreased up to approximately 30% of the eucalyptus in the blend, and then, it increased up to 70% and decreased cubically. The observed behavior for lignin could not possibly have been expected due to uncontrolled random factors.

Figure 3. Functional relationship observed between lignin contents and percentage of *Eucalyptus* sp. in the blend.

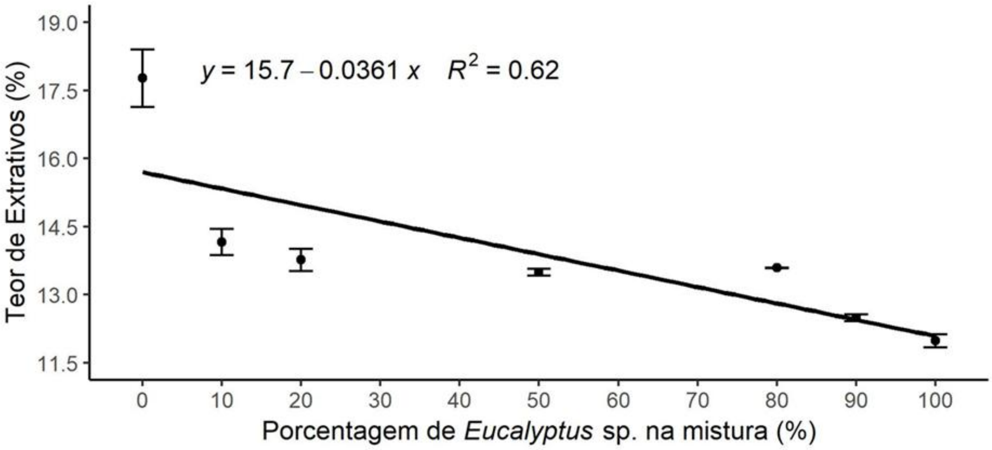


Source: Authors.

For pelletization, higher lignin contents are required because lignin acts as a natural bonding agent between particles, contributing positively to the mechanical properties (Kaliyan; Morey, 2010; Carroll; Finnan, 2012) and the heating value. The values found for the total lignin are consistent with those found in the literature for eucalyptus wood, with a mean value of 24.05%, and for Pinus, with a mean value of 28.45% (Pereira et al., 2016; Siqueira, 2017).

For the level of extractives (Figure 4), the percentage of eucalyptus in the blend had a significant effect. The lowest levels of extractives were found in treatments with 100 and 90% eucalyptus, i.e., those that contained none or the smallest amount of pine in their compositions.

Figure 4. Functional relationship observed between level of extractives and percentage of *Eucalyptus* sp. in the blend.

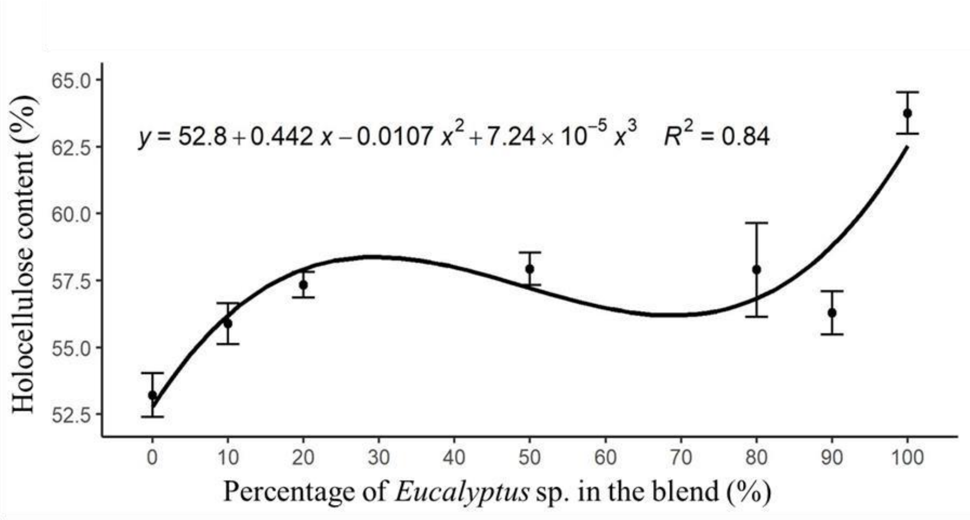


Source: Authors.

Extractives have a double effect on the process of pelletization; they form a weak boundary layer that prevents the particles from bonding strongly but also from producing a lubricating effect, resulting in less friction within the matrix channels (Castellano et al., 2015).

The holocellulose content, which represents the sum of cellulose and hemicelluloses, makes up the highest percentage of the chemical composition of lignocellulosic materials. There was a significant effect on the percentage of eucalyptus in the blend (Figure 5). The pattern of the relationship found is dependent on the results of the lignin content, the total extractives, and the ash because the treatments with higher lignin contents and extractives resulted in a lower holocellulose content, as observed for the materials with 10 and 0% eucalyptus (Treatments 6 and 7, respectively).

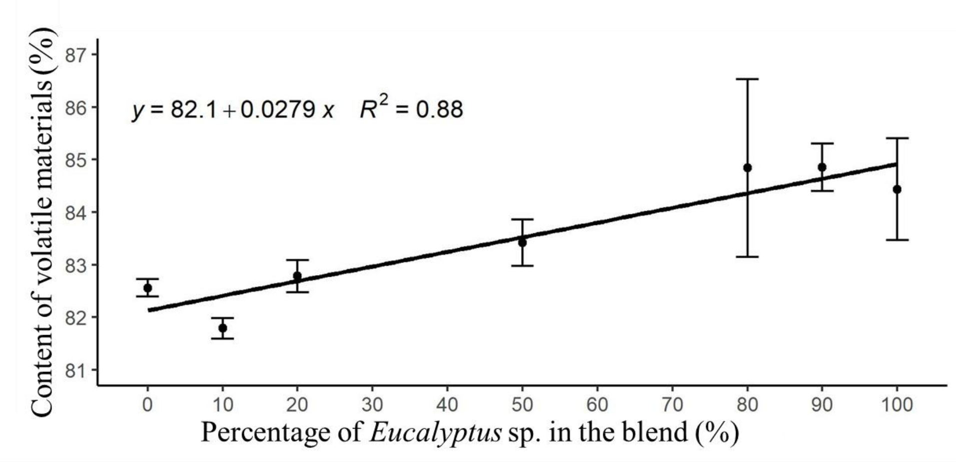
Figure 5. Functional relationship observed between holocellulose content and percentage of *Eucalyptus* sp. in the blend.



Source: Authors.

The results of the regression for volatile materials are shown in Figure 6. High values of volatile materials are favorable because they contribute decisively to help in the ignition of the fuel (Poddar et al., 2014); this assistance occurs because at the time of combustion, CO_2, CH_4 and H_2 are emitted, facilitating the ignition of the pellets. The values found are consistent with those described by Sette et al. (2018) for *Eucalyptus urograndis* wood, whose values were 83.1%, 0.3% and 16.7% for volatile, ash and fixed carbon materials, respectively. They also agree with the mean values reported by Protásio et al. (2015) for Pinus residual wood pellets, which were 84.5%, 0.3% and 15.2% for volatile materials, ash, and fixed carbon, respectively.

Figure 6. Functional relationship between the content of volatile materials and the percentage of *Eucalyptus* sp. in the blend.

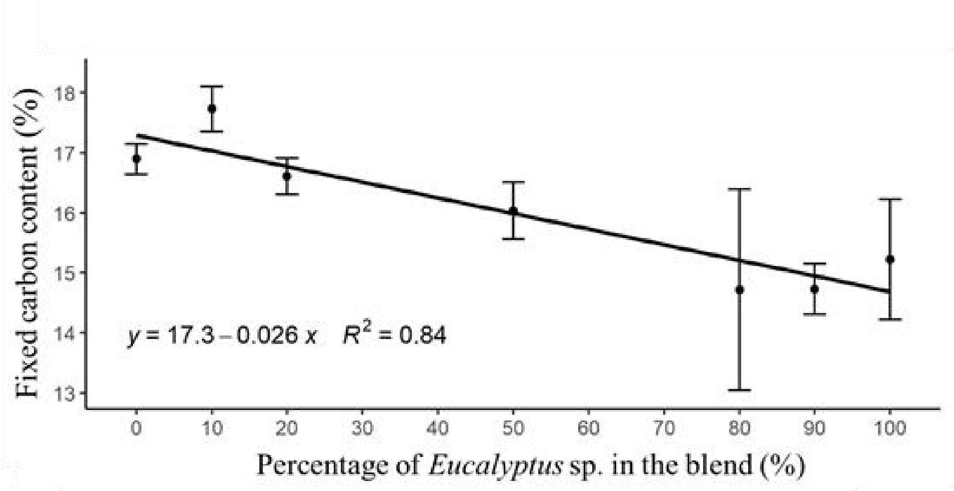


Source: Authors.

It can be inferred that blend with 90 and 80% eucalyptus resulted in pellets with lower ignition temperatures because the greater amount and rapid emission of volatile materials are factors that contribute decisively to accelerating the ignition of the fuel at lower temperatures (Moon et al., 2013).

In contrast, other fuels with a higher fixed carbon content (Figure 7) tend to burn more slowly, have a higher thermal stability, and have a higher-than-mean ignition temperature.

Figure 7. Functional relationship for fixed carbon content and percentage of *Eucalyptus* sp. in the blend.

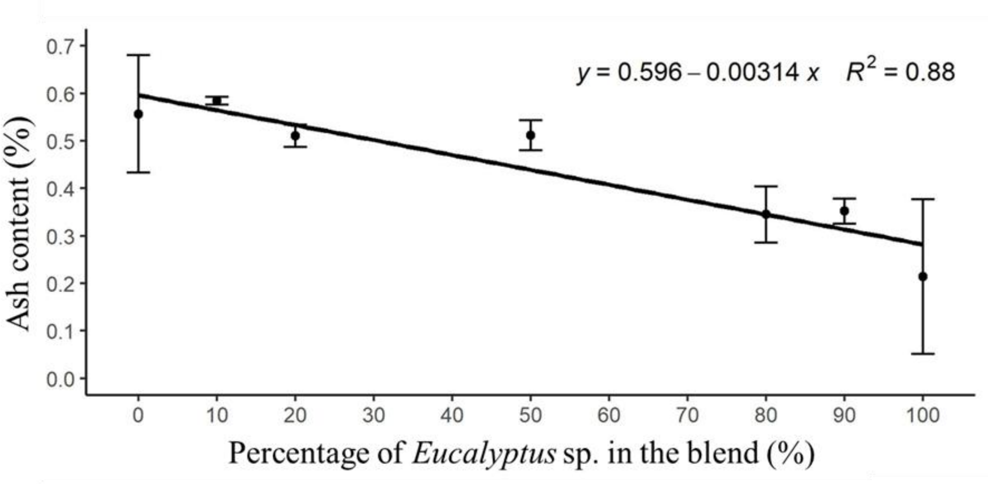


Source: Authors.

The fixed carbon content ranged from 14.72% (80% eucalyptus, Treatment 3) to 17.73% (10% eucalyptus, Treatment 6). The best results were found for 20, 10 and 0% eucalyptus (Treatments 5, 6 and 7, respectively).

The ash content (Figure 8) was slightly higher in the treatments with higher quantities of pine in the blend. This outcome may occur because particles from sawmill waste are more susceptible to contamination during material processing. The eucalyptus particles come from processing the hulled wood, which is performed in the company with due care.

Figure 8. Functional relationship between ash content and percentage of *Eucalyptus* sp. in the blend.



Source: Authors.

Ashes are undesirable components in industrial processes and, mainly, in the domestic use of biomass (residential heating). Many studies have pointed to ash as a component that can assist in the prediction of HHV (Cordero et al., 2001; Shen et al., 2010). However, this negative relationship between ashes and HHV did not occur in this study. The increase in ash content was not sufficient to negatively affect the higher heating value.

The low ash content is one of the characteristics of eucalyptus, which makes it viable for use as an energy source when values are below 1% (Gominho et al., 2012) because a high ash content is a parameter that can determine the exclusion of the raw material for pellet production (Pereira, 2014).

Chlorine is not part of the chemical composition of wood and is mainly present due to contamination with precipitation water from tropical regions. This water comes mainly from oceans with a high evaporation and molar concentrations of inorganic ions, containing the chlorine element, at high rates (NaCl), which are absorbed in the biomass during its growth process (Stumm & Morgan, 1970; Riley & Chester, 1971; Keene et al., 1986; Mello, 2001).

Chlorine triggers the formation of compounds such as HCl, dioxins and furans, in addition to causing corrosion in the internal metallic parts of boilers and chimneys (Escobar, 2016).

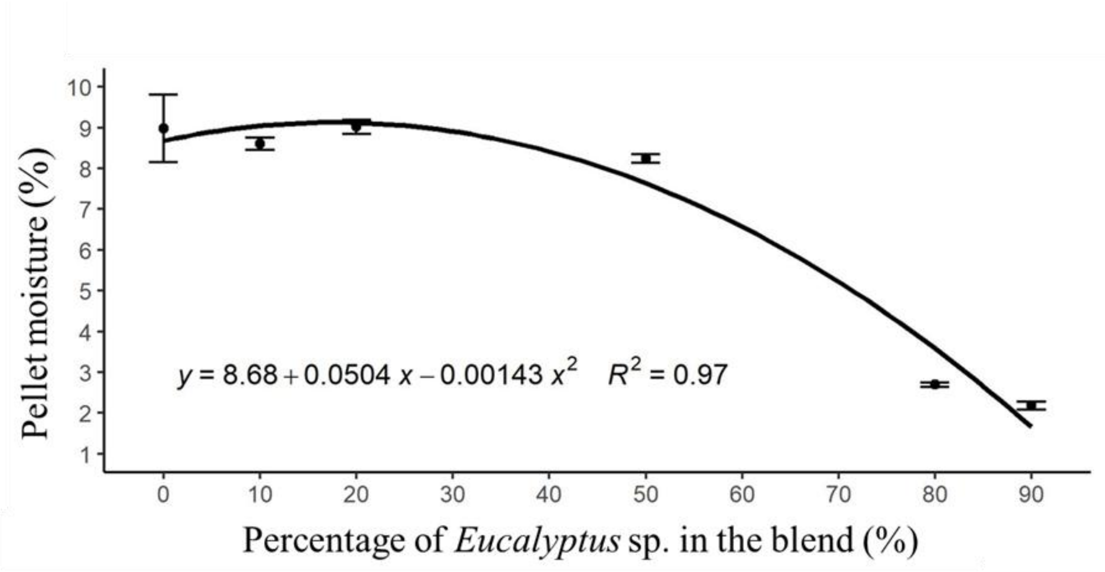
The chlorine contents of *Eucalyptus* sp. and *Pinus* sp. were less than 10 µg · g-1 (microgram of the element per gram of sample). This outcome indicates that the material used is feasible, in this regard, for pelleting because it meets the requirements of the main international standards for the marketing of wood pellets—for example, ISO 17225-2 (2013), which establishes a value lower than or equal to 0.02% chlorine in the sample.

3.2 Characterization of pellets

The moisture of the treatments decreased from 16 ± 2% to values below 10% (dry basis) because part of the moisture of the biomass is lost through the friction heat developed in the matrix due to compression and extrusion. The low moisture content in the pellet production is recognized as an important parameter for rationalizing long-distance transportation systems from Brazil to Europe (Cavalett et al., 2018).

The regression results (Figure 9) showed a significant effect for the percentage of eucalyptus. A greater difference in the moisture was observed for Treatments 2 and 3 (90 and 80% eucalyptus, respectively) in relation to the others. This difference most likely occurred because these treatments had higher retention times in the pelletizer due to the greater hardness of the material (greater percentage of eucalyptus) and, consequently, a higher friction and temperature inside the matrix (Filbakk et al., 2011; Larsson et al., 2008).

Figure 9. Functional relationship between pellet moisture and percentage of *Eucalyptus* sp. in the blend.

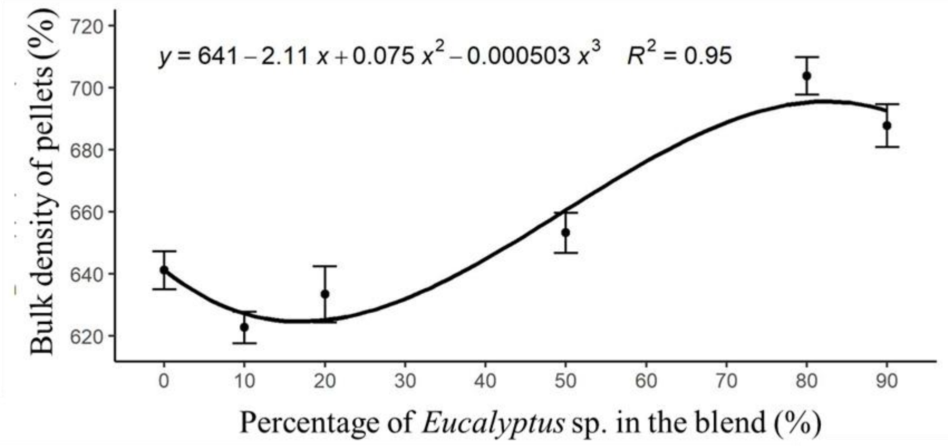


Source: Authors.

Thus, a higher initial moisture content decreases the friction, which results in a reduced matrix temperature (Filbakk et al., 2011) and a decrease in the use of electric energy.

Regarding the bulk density of the pellets (Figure 10), higher bulk density values were observed for treatments with higher percentages of eucalyptus (90 and 80% eucalyptus), which coincide with treatments with lower biomass bulk densities pelletization.

Figure 10. Functional relationship between the bulk density of pellets and the percentage of *Eucalyptus* sp. in the blend.



Source: Authors.

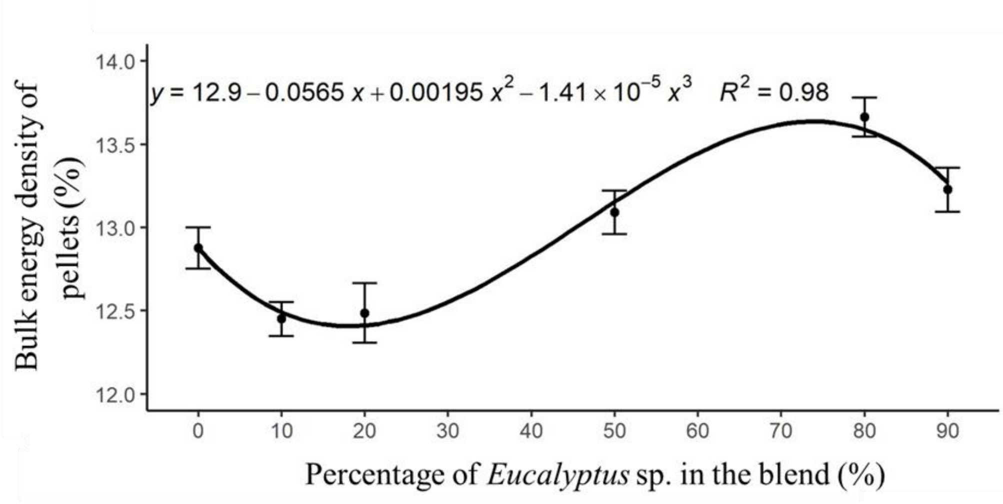
In this regard, it is desirable to obtain higher bulk density values because factors such as transportation costs and energy density are essential in the economic viability of biomass energy use; indeed, they allow for more energy per unit volume to be transported (Stelte et al., 2011).

The energy density indicates the amount of energy stored per material volume (Sette et al., 2016). Bulk energy density is a function of the bulk density of pellets and HHV. Therefore, the density can be considered to be the main quality index for the energy use of biomass fuels because it directly influences the energy density (Protásio et al., 2015).

Thus, the bulk energy density that was observed (Figure 11) had a pattern similar to that observed for the bulk density.

The bulk energy density of the pellets behaved in a cubic manner. It decreased until there was an approximately 20% proportion of eucalyptus in the blend, grew until having nearly 80% eucalyptus and decreased again until the treatment had 90% eucalyptus.

Figure 11. Functional relationship between the bulk energy density of pellets and the percentage of *Eucalyptus* sp. in the blend.

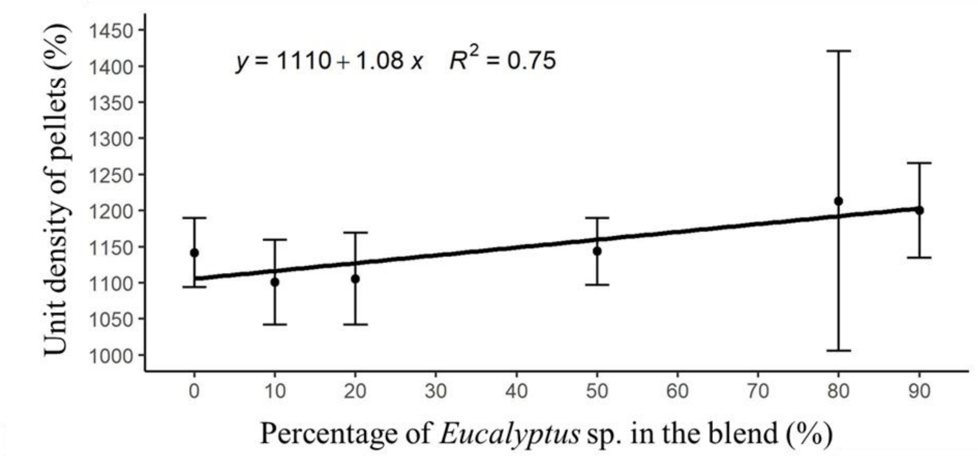


Source: Authors.

Regarding the bulk density of the pellets, higher values were observed in relation to the bulk density because the empty spaces between the pellets were not considered for the calculation of the bulk density. A better adhesion results in a higher unit density of the pellets because they expand less compared to pellets with poor bonds between the particles.

The unit density of the pellets was significantly influenced linearly by the percentage of eucalyptus in the blend (Figure 12). As occurred for the bulk density, the highest values of the unit density correspond to 90 and 80% proportions of eucalyptus in the blend, with 1200.3 and 1213.3 kg m-3, respectively.

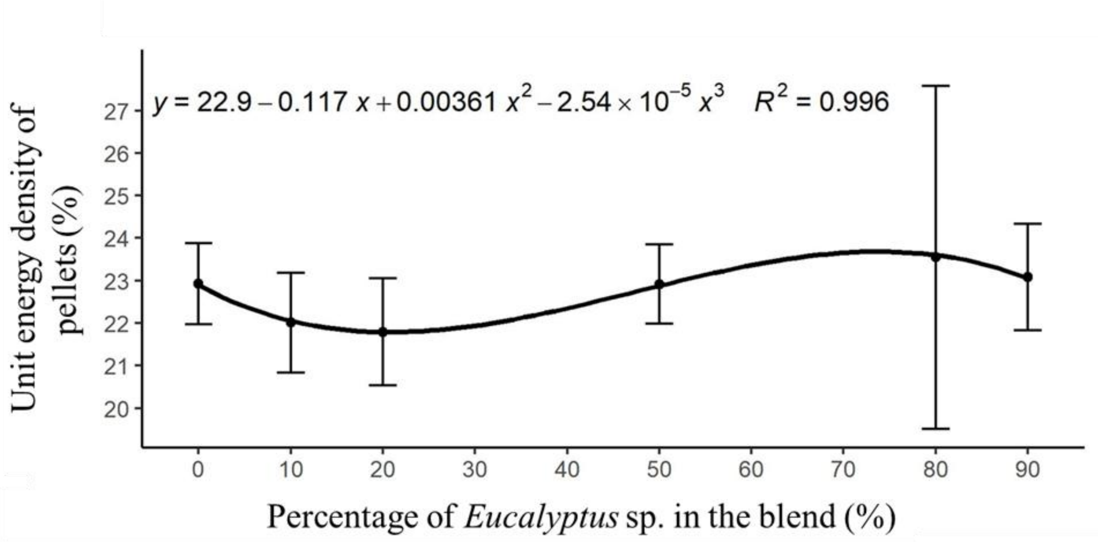
Figure 12. Functional relationship between the unit density of pellets and that of *Eucalyptus* sp. in the blend.



Source: Authors.

As for the bulk energy density, the unit energy density depends on the HHV. The fitted curve for the unit energy density of the pellets is shown in Figure 13. The behavior of this property was similar to that of the bulk energy density for all treatments.

Figure 13. Functional relationship between the unit energy density of pellets and the percentage of *Eucalyptus* sp. in the blend.



Source: Authors.

Pellets with higher bulk energy density and higher unit density values have a direct influence on transportation and storage because fuels with higher energy densities allow for optimizing transportation, reducing costs, and increasing the transportation distance, in addition to storing greater amounts of energy per transportation volume over a long period of time. Treatments 2 and 3 (90 and 80% eucalyptus, respectively) are thus highlighted due to the higher mean values obtained, with 23.54 and 23.08 gJ m-3, respectively.

The mean values of the compaction rate of the treatments are presented in Table 2. Note the higher compaction rate in treatments 2 and 3, which are responsible for the higher percentages of eucalyptus in its composition and the lower bulk densities of the biomass before pelletization.

Table 2. Average values of the compaction rate for each treatment.

Treatments	*Eucalyptus sp.* Percentage (%)	Compression Rate
2	90	3,38
3	80	3,50
4	50	3,05
5	20	2,81
6	10	2,74
7	0	2,66

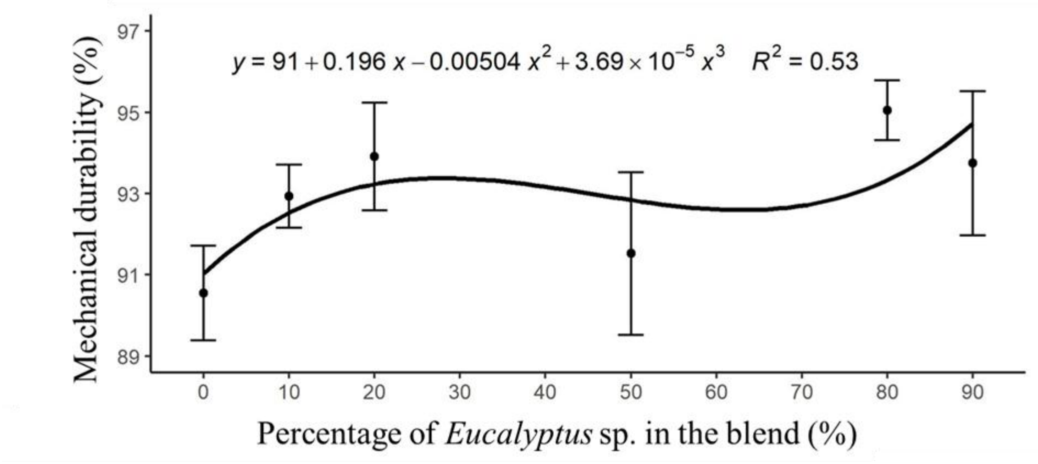
Source: Authors.

According to Protásio et al. (2011), the lower the bulk density of the biomass is, the greater the percentage increase of its density after compaction and consequently the better the particle accommodation.

When there is a greater compaction of the material, the contact area between the biomass particles is larger;

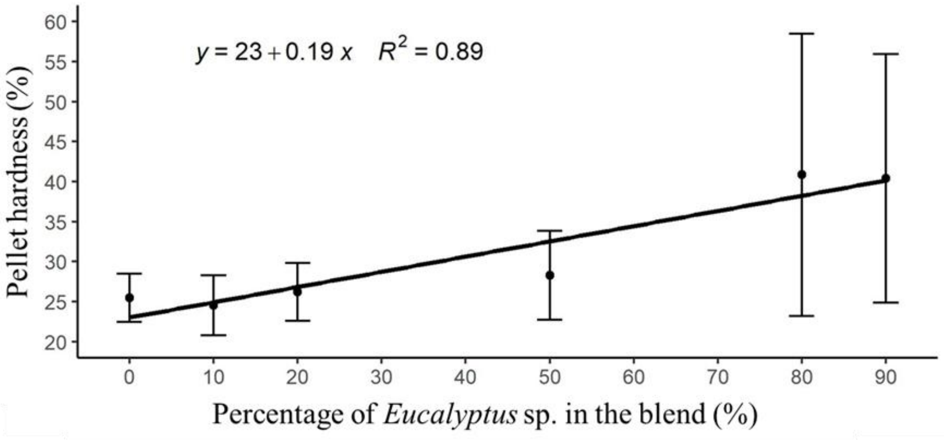
consequently, the mass per unit volume increases, and in general, the pellets will have a greater mechanical strength (Zamorano et al., 2011; Pereira, 2014). This outcome is shown in Figures 14 and 15, which present the results of mechanical durability and hardness, respectively. The treatments responsible for the greatest durability and hardness are also the ones with the highest compaction rate.

Figure 14. Functional relationship between the mechanical durability of pellets and the percentage of *Eucalyptus* sp. in the blend.



Source: Authors.

Figure 15. Functional relationship between pellet hardness and percentage of *Eucalyptus* sp. in the blend.



Source: Authors.

Regarding the mechanical properties of the pellets produced, the fine content had no significant effect on the percentage of eucalyptus in the biomass blend. The mean value found in this item was 0.08%. All values found are lower than those specified by ISO 17225-2 (2013), which allows for up to 1% fines.

Durability indicates the integrity of the pellets during storage and transportation (Tumuluru, 2016). The results of the regression analysis (Figure 14) indicate that the mechanical durability behaved in a cubic manner. Note that the durability obtained for Treatment 3 (80% eucalyptus) was higher than Treatment 2 (90% eucalyptus), a fact that can be explained by the higher compaction rate and densities of this treatment.

According to Wongsiriamnuay and Tippayawon (2015), densification affects the properties and fuel quality, and the variables controlled during the process influence the density and durability of the product. High palletization temperatures provide greater durability to the densified material and require higher energy consumption and higher operating expenses.

The hardness is directly related to the bulk density of the pellets (Zamorano et al., 2011) and simulates compression due to the weight of the pellets themselves during storage or transportation. Note that the increase in the hardness (Figure 15) of the pellets due to the increase in the percentage of eucalyptus occurred linearly.

4. Conclusion

The raw materials used proved to be suitable for producing pellets for export due to the stringent requirements of ash and chlorine contents, which represent a great obstacle for the use of certain biomasses.

The treatments with the highest percentage of eucalyptus presented the best results, mainly in terms of mechanical properties, with emphasis on Treatment 3, which presented the best performance in terms of density and mechanical characteristics, although no treatment was able to meet international standards regarding mechanical durability.

This demonstrates that eucalyptus pelletization requires some adjustments in the process and conditioning of the raw material, which we recommend being considered in future studies.

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