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Limitations of bamboo and sugarcane pellets in domestic and industrial systems

Limitações dos pellets de bambu e cana-de-açúcar em sistemas domésticos e industriais

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ABSTRACT: The need to replace fossil fuels with low carbon sources has intensified the intercontinental trade in sustainable energy. However, some vegetable biomasses have energy characteristics that limit certain applications for biofuels production, specially the pellets. The objective of this work was to present these limitations of bamboo and sugarcane bagasse pellets, compared to the parameters required by the standard of the International Organization for Standardization. The study evaluated the energy properties of three types of pellets: pine, sugarcane bagasse and bamboo. It was performed the elementary analysis, immediate analysis, as well as the higher heating value, mechanical durability, energy density, bulk density and residual ash were also assessed. The results revealed negative aspects of agropellets compared to wood pellets: higher ash content, less energy released, low mechanical durability and more content of silica in the residual ash, which can cause incrustations in the burner equipment. Sugarcane bagasse pellets had the highest ash content (4.78%), the lowest higher heating value (18.52 MJ kg^{-1}) and the highest SiO_2 content in the residual ash (60.23%). The higher levels of chlorine in bamboo and sugarcane bagasse pellets indicate a greater possibility for the formation of slag and incrustations in the burning equipment.

Keywords: Agropellets; Ashes; Chlorine; Fouling inclinations; Slagging.

RESUMO: A necessidade de substituição de combustíveis fósseis por fontes de baixo carbono intensificou o comércio intercontinental de biocombustíveis pellets. No entanto, algumas biomassas vegetais têm características energéticas que restringem determinadas aplicações dos agropellets. O objetivo deste trabalho é apresentar essas limitações dos pellets de bambu e bagaço de cana, comparativamente aos parâmetros exigidos pelo padrão da Organização Internacional de Padronização. O estudo das propriedades energéticas de três tipos de pellets (pinus, bagaço-de-cana e bambu) foi realizado a partir da análise elementar, análise imediata, poder calorífico superior, durabilidade mecânica, densidade energética, densidade a granel e cinzas residuais da combustão. Os resultados revelaram aspectos negativos dos agropellets comparativamente aos wood pellets: maior teor de cinzas, menor quantidade de energia liberada, baixa durabilidade mecânica e cinzas residuais com mais sílica, que podem causar incrustações e desgastes nos queimadores. Os pellets de bagaço de cana apresentaram o maior teor de cinzas (4,78%), o menor poder calorífico superior (18,52 MJ kg^{-1}) e o maior conteúdo de SiO_2 nas cinzas residuais da combustão (60,23%). Os teores de cloro mais elevados nos pellets de bambu e bagaço de cana indicam maior possibilidade de formação de escórias e incrustações nos equipamentos de queima.

Palavras-chave: Agropellets; Cinzas; Cloro; Escórias; Incrustações.

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1 INTRODUCTION

In the face of many natural disasters caused by climate change, there is a worldwide mobilization to accelerate the energy transition in search of more sustainable energy sources (Souza *et al.*, 2020). The recommended migration to low carbon energy, using pellets from biomasses, has already modified the energy matrix of many European countries that need to reduce their polluting emissions of greenhouse gases (GHG). For example, the UK's Drax Power thermoelectric, using these biofuels, reduced its carbon footprint by 80% compared to mineral coal, which now represents only 6.0% of the plant's energy production (Quéno *et al.*, 2019).

This intense intercontinental trade in pellets is only possible due to the high energy density (ED) of these biofuels (14.0 GJ m^{-3}), which provides considerable logistical gains in storage and handling, favoring to transport a greater mass of pellets with smaller volume in the cargo compartment (García *et al.*, 2018). However, other energy characteristics are important in assessing the quality of a solid biofuel and can limit its applications, such as high ash content, low higher heating value and mechanical strength (Quéno *et al.*, 2019; Silva *et al.*, 2020; Souza *et al.*, 2020)

Significant research points the great Brazilian potential for production of biomass pellets due to the high content of residues generated from agricultural and forestry activities. Bonassa *et al.* (2018) estimated 298 million t per year of residual biomass from processing rice, sugarcane, corn, soybeans and wheat and 6 million m^3 of waste generated from the harvesting of pine and eucalyptus forest. However, pellets from Brazilian lignocellulosic biomass (elephant grass, sugarcane bagasse) have limitations for the energy use of domestic and industrial equipment, due to the low mechanical durability and high levels of nitrogen and ash (Souza *et al.*, 2020)

Grass agropellets (sugarcane bagasse and bamboo) have higher ash content than pellets from forest raw material (i.e. pine) due to different organic structures, faster metabolism and absorption of more nutrients during plant growth periods. High levels of these inorganic elements cause technological and environmental challenges during the conversion of solid biofuel, such as the formation of slag in the furnaces, incrustations on the surfaces of the heat exchangers, corrosion in the burners and formation of soot (Vassilev *et al.*, 2017).

The higher ash content, besides causing damage to the boilers, reduces the heating value of the pellets (Silva *et al.*, 2020). Higher heating value is a measure of the chemical energy released during the combustion of biomass, which is considered the most important property to characterize a material as a fuel (Souza *et al.*, 2020). In studies with eucalyptus, elephant grass and sugarcane bagasse, the authors concluded that is possible to mixture several lignocellulosic biomasses to reduce the ash content of the pellets and increase the amount of energy released during burning. Thus, the mixtures are examples of how to overcome the limitations imposed by biofuels that have a higher ash content and lower heating value (García *et al.*, 2019).

The content of some elements, such as Ca, K and Cl in the ash content in agricultural and forest biomass can cause a decrease in the combustion efficiency of these raw materials in residential and industrial systems (Vassilev *et al.*, 2017). The problems caused by combustion device (slagging, fouling, bed agglomeration, and corrosion) depends on the composition of the ash (inorganic materials) and its properties (Magdziarz *et al.*, 2018). For example, the basic components Na_2O, K_2O, MgO, CaO and Fe_2O_3 reduce the melting temperature of the ash, while the acidic oxides SiO_2, Al_2O_3 and TiO_2, tend to increase it.

The study of these limitations presented by agroforestry pellets is important to direct a better application (residential, commercial or industrial), in addition to discussing ways and technologies that allow to overcome technical challenges for their use, since in Brazil there is great availability and variety of plant biomass that can be compacted to produce the pellets (García *et al.*, 2018). There are several scientific studies concerning the characterization of biofuel pellets produced from cultivated biomasses, for example, in Spain - blends of pine sawdust with coffee wastes (García *et al.*, 2019), Chile - wheat straw (Azócar *et al.*, 2019), Pakistan - rice husk (Iftikhar *et al.*, 2019) and China - rice straw (Xia *et al.*, 2019). However, there are scientific gaps regarding the quality of pellets produced with Brazilian biomass, especially regarding the chlorine content and ash composition resulting from combustion.

In this context, the objective of this research is to present and discuss the limitations of biomasses such as bamboo and sugarcane bagasse for production of pellets, comparing to pine biomass, mainly in terms of ash content and composition, chlorine content and the amount of energy released in the combustion.

2 MATERIAL AND METHODS

2.1 OBTAINMENT OF THE PLANT BIOMASS AND PRODUCTION OF THE PELLETS

Approximately 20 kg of pellets were produced from each type of biomass: pine, bamboo and sugarcane bagasse (Figure 1). The original plant biomasses were reduced into particles up to 50.0 mm and dried at room temperature (± 21 °C), and arranged in 40.0 mm thick layers until reach approximately 15% of moisture content (dry basis). Posteriorly, they were milled in a willey hammer mill containing a sieve with opening of 4.0 mm to obtain particles with suitable dimensions to produce pellets.

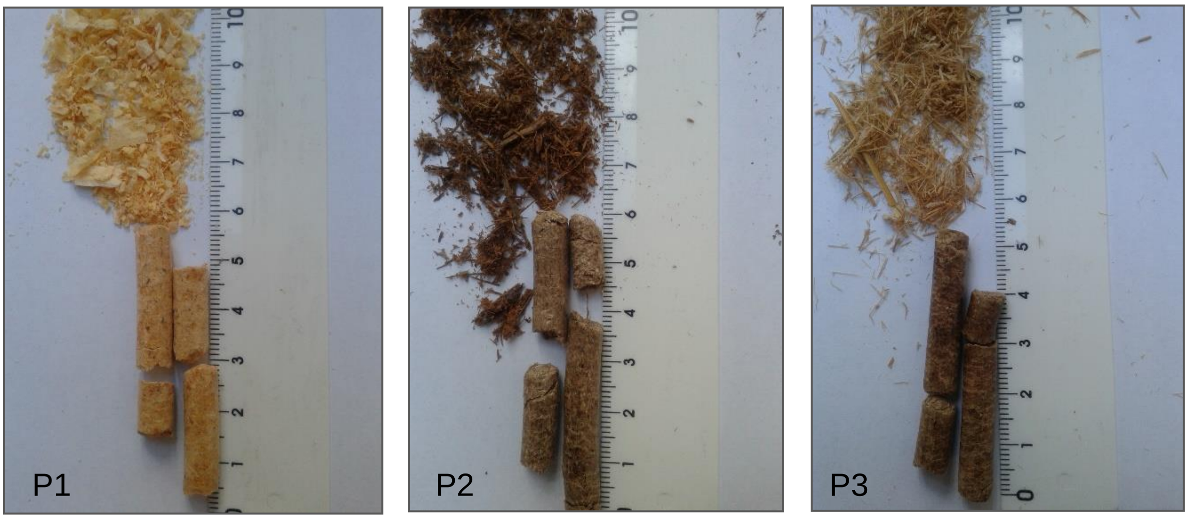

Figure 1. Pellets produced from biomass: P1: pine; P2: sugarcane bagasse; P3: bamboo

The Florpinus Florestal pellet industry offered their infrastructure, located in Itapeva city, state of São Paulo, for the manufacture of samples. A horizontal type industrial pelletizer was used in the process, with a capacity to produce 1.0 t h^{-1} of pellets and has channels with a diameter and length of 6.0 and 40.0 mm, respectively. It was pre-heated gradually over 30 minutes until reach approximately 90 °C, maintaining this average temperature throughout the production process. The raw material used to prepare the pellets was collected from different regions of Brazil:

- P1 Pine (*Pinus* spp.), with debarked wood obtained from a furniture industry of Sengés city, state of Paraná;
- P2 Sugarcane bagasse (*Saccharum officinarum*), material composed with stems, obtained from the sugar/alcohol plant in the Itaí city,state of São Paulo;
- P3 Bamboo (*Dendrocalamus asper*), with stems and leaves, obtained in Goiânia city, state of Goiás.

2.2 CHARACTERIZATION OF THE VEGETAL BIOMASS PELLETS

For chemical characterization, the pellets were ground, transformed into sawdust and the analyzes carried out in the fraction classified between sieves of 40 (0.42 mm) and 60 (0.25 mm) mesh. The immediate chemical composition of the pellets was carried out following the procedures of the American Society for Testing and Materials (ASTM) D1762 (ASTM, 2001) standard, with fixed carbon content (FC) obtained by difference. For the ash content, the pellets were crushed in a Willey mill and 1.0 g of the particles that passed through the 50-mesh sieve (0.297 mm) was taken to the digital electric muffle. The samples remained in this equipment for five hours, with an initial temperature of 30 °C, heating rate of 4.5 °C min^{-1}, increments of 50 °C every 30 minutes and a final temperature of 550 °C, according to the methodology established by the International Organization for Standardization (ISO) in its standard 18122 (ISO, 2015). The moisture content (MM) was performed according to the standard NBR 14929 of the Brazilian Association of Technical Standards (ABNT, 2017).

The elementary analysis of the pellets was performed on a CHNS/O Perkin Elmer 2400 analyzer, which uses helium and oxygen as carrier and ignition gases, respectively. The equipment analyzed levels of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S), performed by the ASTM standards (2008a, 2008b, 2008c). The test was performed with 2.0 mg of material with granulometry <1.0 mm and free from moisture were used. The oxygen content (O) was obtained by difference, about the other elementary components.

The higher heating value (HHV) of the pellets was determined with an IKA WORKS C-5000 isothermal digital calorimeter, using the methodology established in TS 14918 standard (2005). The energy density (ED) was obtained from the product between the HHV and the bulk density (BD) of the pellets, according to the procedures of TS 15103 standard (2005b). For these tests, a cylindrical PVC container was used, with total volume of 5 L, and a relation between the height (228 mm) and the diameter (167 mm) of approximately 1.37, as specified in the referred regulation.

The requirements for testing the mechanical durability (DU) of the pellets are defined in the technical specifications TS 15210 (2005c). The pellets (500 g) are positioned inside a rotating box with dimensions of 300 x 300 x 125 mm, at a speed of 50 rpm, for 10 minutes. Then, the sample passed through a sieve with an opening of 3.15 mm. The mechanical strength indicator was the percentage between the mass of intact pellets about the total mass of the sample.

For the characterization of the residual ash from the combustion process, approximately 10.0 g of each sample (P1, P2 and P3) were collected and aliquots of 0.5 g were separated from each one. These samples were melted with lithium tetraborate ($Li_2B_4O_7$) in platinum crucibles, forming tablets that were sent to the company ELFUSA - Eletrofusão Geral Ltda, specialized in general electrofusion, in São João da Boa Vista – state of São Paulo, where it was analyzed with an X-ray fluorescence PANALYTICAL spectrometer, model Axios PW4400/40. The analyses carried out in this equipment allow the detection of elements in form of oxides such as SiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, TiO_2 and P_2O_5. To calculate the slag viscosity index (Sr), the methodology adopted by Garcia-Maraver *et al.* (2017) was used according to Eq. 1.

$$Sr = \frac{SiO_2 \times 100}{SiO_2 + Fe_2O_3 + CaO + MgO} \qquad (1)$$

This index calculates the percentage of silica in the residual ash, excluding alkaline compounds. High values of this index correspond to high viscosity and, therefore, low tendency to form silica residue.

For the classification of different types of pellets, the biomass classification index was used according to Souza *et al.* (2020). The fuel value index (FVI) was estimated using Eq. 2.

$$FVI = \frac{HHV \times BD}{A} \qquad (2)$$

where FVI is the fuel value index; HHV is the higher heating value (MJ kg^{-1}); BD is the bulk density (g cm^{-3}); and A is the ash (g g^{-1}).

2.3 STATISTICAL ANALYSIS

All tests were performed in triplicate, except for mechanical durability, which was performed in five repetitions. The variability of the data and the behavior of the original variables were evaluated with descriptive analysis of the pellets and determination of parameters of central tendency and dispersion. The analysis of variance (ANOVA) was performed and, for comparison between the averages, the Tukey test was carried out, with a 5% of significance level.

3 RESULT AND DISCUSSION

The descriptive statistics of the three types of pellets (Table 1) demonstrated a wide range of values for all the properties evaluated. Pellets are biofuels that generally have humidity below 10%, as determined by international quality standards. In this study, the three treatments met this criterion and the average results showed no statistically significant difference according to the Tukey test at 5%. In general, pine wood pellets showed better physical, chemical and mechanical properties compared to pellets produced with agricultural biomass. Pine pellets are important comparative references because, in most cases, they meet all the quality requirements listed for type A1 EN Plus pellets of the international standard ISO 17225 (ISO, 2014).

The volatile matter (VM) of bamboo and sugarcane bagasse pellets did not show significant statistical differences. The values between 79.61 and 81.71% are consistent with the literature for these biomasses (García *et al.*, 2019). It was observed that the pine pellets had the highest average content of volatile matter and, consequently, the highest higher heating value, corroborating the results reported by (Silva *et al.*, 2020).

The average content of fixed carbon of pine pellets was higher in comparison to sugarcane and bamboo bagasse pellets, which did not show statistically significant differences by the Tukey test. In practical applications, the low FC index of bamboo and sugarcane bagasse pellets will provide faster combustion, resulting in a shorter residence time for solid biofuels in the burning equipment (Garcia; Caraschi; Ventorim, 2017).

Table 1. Average energy characteristics of pellets produced with plant biomass

Variables	**P1**	**P2**	**P3**
	Pine	**Sugarcane bagasse**	**Bamboo**
Volatile matter (%)	81.71 (±1.23)a	79.61 (±1.60)a	80.60 (±0.80)a
Fixed carbon (%)	17.97 (±0.45)a	15.62 (±1.34)b	16.44 (±0.67)b
Moisture content (%)	7.62 (±0.91)a	8.20(±0.75)a	6.97(±0.86)a
Carbon (%)	49.44 (±0.25)a	46.00 (±0.31)b	47.02 (±0.35)c
Oxygen (%)	43.18 (±0.28)a	46.50 (±0.37)b	45.58 (±0.39)c
Hydrogen (%)	6.48 (±0.08)a	6.21 (±0.14)b	6.11 (±0.04)b
Nitrogen (%)	0.82 (±0.10)b	1.21 (±0.07)a	1.22 (±0.08)a
Sulfur (%)	0.075 (±0.008)a	0.078 (±0.005)a	0.066 (±0.007)b
Mechanical durability (%)	97.90 (±1.2)a	87.54 (±3.1)b	90.29 (±2.3)b
Energy density (GJ m^{-3})	14.25 (±0.19)a	10.74 (±0.15)b	14.26 (±0.16)a
Bulk density (kg m^{-3})	689.90 (±15.4)a	579.90 (±30.3)b	726.20 (±21.6)a

Note: Means followed by the same lowercase letter on the line do not differ at 5% significance by the Tukey test. Values in parentheses refer to the standard deviation (Garcia *et al.*, 2019).

Regarding the ash content, a great difference was observed among the three types of pellets evaluated. The low index of residual mineral elements allows us to infer that pine pellets are classified as Premiun A1 EN Plus. according to international quality standards ISO 17225 (ISO, 2014). The sugarcane bagasse and bamboo pellets, on the other hand, did not meet the requirements of the European pellet quality standard for domestic use, being recommended only for industrial applications. For this reason, in this international standard, they are classified as industrial type B non-wood pellets.

The sugarcane bagasse and bamboo pellets from agricultural biomass showed ash content approximately 15 and 9 times higher than the pine wood pellets (Figure 2). The high ash contents of these pellets limit their application in bakery and pizzeria ovens. The volume of residual ash generated could deposit on the food, contaminating it, when the bread or pizza are in the same burning environment (Magdziarz *et al.*, 2018). In addition, consumers reject pellets with high ash contents, arguing that they cause incrustations and corrosions on the surfaces of the pipes, promoting excessive dirt on the burners and the need for higher maintenance expenses (Garcia; Caraschi; Ventorim, 2017).

Regarding the elementary analysis (C, H, O, N and S), it can be inferred that the pine pellets had higher levels of carbon and hydrogen. In the practical applications of biofuels pellets, these characteristics are important to produce bioenergy, due to the individual energy value of these elements and the positive correlation with heating value (Christoforou; Fokaides, 2017). On the contrary (Table 1), high levels of oxygen, found in sugarcane bagasse and bamboo pellets decrease the heating value of these biofuels (García *et al.*, 2018).

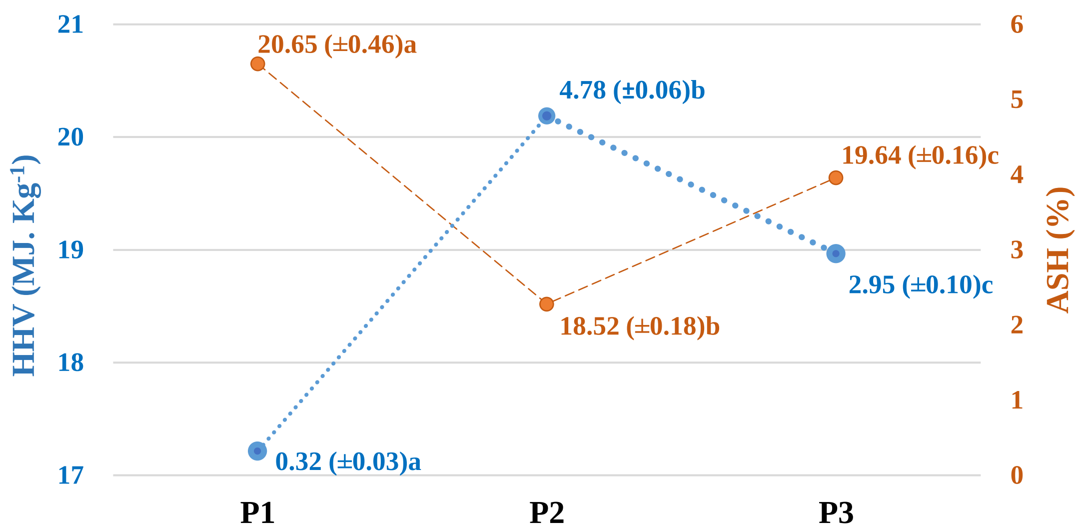

Figure 2. Relationship between higher heating value (HHV) and ash content of pellets

Sulfur and nitrogen are more associated with environmental pollution (NO_x and SO_x emissions) than to the generation of thermal energy. The nitrogen content of bamboo and sugarcane bagasse is higher when compared to the pine, favoring the formation of nitrous oxides. From the point of view of energy generation in industrial systems, high levels of nitrogen would require specific health and safety procedures, such as scrubbers to capture polluting emissions (Whottaker; Shield, 2017) Thus, industrial applications are limited for agropellets produced with vegetal biomasses with high levels of nitrogen and sulfur.

HHV is an important indicator of pellet quality and reveals its potential for generating thermal energy. The heating value depends on the chemical composition of the vegetal biomass (cellulose, hemicelluloses and lignin) and has an inverse correlation with the ash content (Figure 2), that is, the higher is the ash content, lower the amount of energy released in combustion of lignocellulosic biomass (García *et al.*, 2018). For this reason, the HHV of pine pellets, which has only 0.32% of ash, was higher than that observed for sugarcane bagasse and bamboo pellets. It was found that biomasses with a high content of volatile matter and low ash contents have higher heating value (Silva *et al.*, 2020). This study confirmed this statement since the higher heating value of the pellets presented the following order: P1> P3> P2.

The FVI results confirm the influence of the type of lignocellulosic material on the physical, chemical and energy properties of the pellets. Pine, bamboo and sugarcane bagasse pellets presented FVI of 4452; 484; 225, respectively. Higher FVI values indicate pellets with better energy properties, easier ignition and higher levels of volatile matter and carbon (Souza *et al.*, 2020). In the present study, sugarcane bagasse pellets showed low energy performance compared to bamboo and pine wood pellets. Sugarcane bagasse pellets showed FVI 95% lower than that found for pine pellets. This result can be attributed to the higher ash content and lower heating value and density of sugarcane bagasse pellets, showing low energy quality of this biofuel when compared to P1 Pellets.

Several parameters interfere in the mechanical strength of the pellets. Whittaker and Shield (2017) concluded that the high lignin content, ideal moisture content between 10 and 15%, combined with high temperature of the pelletizer, tend to improve the mechanical durability (DU). To offer the same process conditions and minimize interference from external variables, such as the temperature of the pelletizer, the samples were produced by the same equipment, under the same conditions of temperature, pressure and rotation speed of the matrix.

The moisture of the three types of raw material showed no statistically significant difference, thus, the high difference observed between the DU of pine pellets compared with bamboo and sugarcane bagasse may be related to the adjustment of the equipment to the density of the lignocellulosic material. The mill, where the samples were produced, routinely manufactures pine pellets and uses dry shavings as a raw material. The sugarcane bagasse and bamboo particles density are different from them, requiring a different compaction ratio, which is the reason for the low mechanical strength observed in these pellets. Therefore, the difference in DU is much more due to the lack of adjustment in the pelletizer to the raw material than to the moisture. In practice, these pellets with low durability, are brittle and easily disintegrate in handling, transport and storage, presenting problems in the management and use as biofuels (García *et al.*, 2018).

The volumetric energy density (ED) was calculated by multiplying the higher heating value by the bulk density (BD) of the pellets, as proceeded in previous studies (García *et al.*, 2019). The high ED (representing greater amount of energy per volume) observed in pine and bamboo pellets is one of the advantages of these solid biofuels, as they minimize storage and transportation costs. Accordingly, as higher is the bulk density of the pellets, higher is the energy density. In this way, the low BD of sugarcane bagasse pellets (579.90 kg m^{-3}) also explains its lower ED compared to P1 pellets. In this case, the ED of sugarcane bagasse pellets was 24.63% lower than that observed for the wood pellet.

Table 2 shows a comparison of the chemical composition of the residual ash obtained by X-ray fluorescence. The result reveals a variation in the compositions of inorganic materials, which are presented in the form of mineral oxides. The main components of the ash from the pine pellets (P1) were calcium oxides (CaO) and potassium oxide (K_2O). The ashes of the sugarcane bagasse pellet (P2) mainly include silicon oxide (SiO_2). For the bamboo pellets (P3), there is a predominance of silicon and potassium oxides.

According to Magdziarz *et al.* (2018), the basic components (Na_2O, K_2O, MgO, CaO and Fe_2O_3) reduce the melting temperature of the ash, while acid oxides (SiO_2, Al_2O_3 and TiO_2) tend to increase it. These results show that, in general, forest biomass (P1) contains low silica content, whereas in grasses (P2, P3) substantial amounts of Si were found, converging with the results presented by Vassilev *et al.* (2017).

Table 2. Chemical composition of sample residual ash (dry basis,%)

Biomass	MnO	Fe_2O_3	SiO_2	CaO	MgO	Al_2O_3	K_2O	Na_2O	SO_3	P_2O_5	TiO_2	Cl_2O	Others
P1 (Pine)	3.36	1.17	10.46	30.91	12.14	5.21	19.48	1.53	7.30	7.25	0.19	0.36	0.64
P2 (Bagasse)	0.08	6.50	60.23	1.18	4.97	3.24	16.15	0.26	0.68	3.85	1.17	1.54	0.15
P3 (Bamboo)	0.12	5.78	43.99	4.12	3.67	8.47	25.61	0.53	1.55	2.68	0.80	2.46	0.22

The high percentage of silica in the ashes of sugarcane and bamboo bagasse pellets, which are 4.2 and 5.8 times, respectively, greater than that of pine, causes concern due to an abrasive and slag-forming agent on the burners (Garcia-Maraver *et al.*, 2017). In addition, this high abrasiveness of the material results in excessive abrasion of the pelletizers, decreasing their durability, increasing the maintenance and production costs of biofuels. It is noteworthy that silica is the main component of sand and this suggests that the highest levels of SiO_2, presented in P2 and P3 pellets, may originate from the contamination of the raw material during transportation of these biomasses from the field to the industry (SILVA *et al.*, 2020).

More than 74% of the chemical composition of the residual ash from the three pellets analyzed is formed by oxides such as SiO_2, K_2O, CaO, MgO, Fe_2O_3, and Al_2O_3. According to Vassilev *et al.* (2017), ash from non-woody biomass usually have higher levels of calcium (Ca), potassium (K) and magnesium (Mg), as they are nutrients in vegetables and used in soil fertilization. Chlorine acts as a facilitator in the reactions between potassium and silica, leading to the formation of slag at normal boiler operating temperatures. Therefore, the higher levels of this element in bamboo and sugarcane bagasse pellets indicate a greater possibility to form slag and incrustations in the burners (Vassilev *et al.*, 2017).

The slag viscosity index (Sr) of P1, P2, P3 pellets were 19, 83 and 76, respectively. This indicator was high for sugarcane bagasse and bamboo pellets, that is, the ashes have low viscosity according to the classification of Garcia-Maraver *et al.* (2017), meaning a high tendency to form undesirable slag by these biofuels. On the other hand, the Sr indicator of pine pellets signaled high viscosity and low tendency to form silica residue, showing superior quality solid fuel and noble applications, such as residential heating, for example.

4 CONCLUSIONS

In this work the limitations of using bamboo and sugarcane bagasse pellets for energy production were presented. The following conclusions were drawn: Sugarcane bagasse and bamboo pellets have high ash contents, limiting them to industrial applications; The higher heating value of bamboo and sugarcane bagasse pellets are 4.89 and 10.31% lower than that of pine, respectively; The percentage of silica in the ash of sugarcane bagasse and bamboo pellets is 4.2 and 5.8 times higher than that of pine, showing high abrasiveness of the material, resulting in scaling (in use) and excessive wear of pelletizing dies (in production)

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