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Original Paper

Combustion of Sugarcane Bagasse Pellets Produced with/without Glycerol: Chemical, Thermal and Emission Analyses

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Abstract

Purpose: *Use of agricultural biomass in the form of pellets has gained worldwide prominence in recent decades, as part of the search for cleaner and renewable energy sources. Brazil is the largest sugarcane producer in the world, a fact that also places it as a major producer of residues from processing this crop.* ***Methods:*** *In this study, sugarcane bagasse pellets (SBP100) were handcrafted using glycerol as binder (30% - SBP30G) and, subsequently, analyses of their chemical and thermal properties, as well as those of the thermal decomposition exhaust gases, were conducted.* ***Results:*** *Average temperatures in the combustion range were 213.62±137.07° C (SBP100) and 211.97±86.85 °C (SBP30G). Combustion exhaust gas values were 20.04±0.15% (SBP100) and 19.95±0.19% (SBP30G) for* O_2*; 1739.58±156.17 ppm (SBP100) and 1575±466.85 ppm (SBP30G) for CO; 19.92 ± 2.47 ppm (SBP100) and 17.33±4.69 ppm (SBP30G) for NOx; 341.67±134.37 ppm (SBP100) and 491.67±341.42 ppm (SBP30G) for* CH_4*. SBP30G combustion proved to be less polluting with respect to CO and NOx generation than SBP100, but not for* CH_4*. However, average thermal performance was similar for both.* ***Conclusion:*** *Use of glycerol contributed considerably to the changes in the pellets' physical parameters. Exhaust gas analyses of the combustion of these substrates can serve as a basis for creating safety parameters and public policies to regulate the use of biomass for energy purposes.*

Keywords

Biomass, Sugarcane, Pellets, Combustion, Glycerol

1. Introduction

Energy use is a key determinant in the development of a society. Each country's energy production capacity and consumption are benchmarks within the world economy. Thus, these indicators exert significant influence over other productive sectors, subsequently dictating technological development. Considering that energy availability is decisive for production, discussion of the use, distribution, and generation of this resource becomes an essential subject when regarding its environmental consequences, such as atmospheric pollution and global warming.

Natural decreases in global energy substrates, as well as stronger environmental laws, cause renewable and clean sources to become increasingly tangible and necessary options in this changing scenario. Among the various sources capable of replacing fossil fuels, biomass presents itself as an option with worldwide reach.

Biomass as an energy substrate may eventually account for approximately 19% of the world's energy consumption by the end of 2021 (Biomassa & Florestais, 2020). In developing countries, this percentage may reach 35%. These raw materials (vegetable residues) are basically composed of lignocellulosic materials, due to being basically composed of cellulose and lignin (Quirino et al., 2005).

Brazil is the largest producer and exporter of sugarcane in the world (Garcia et al., 2018; Zanetti et al., 2010). Several factors contribute to this status, such as availability of large areas for cultivation, ease of introduction of new and advanced technologies in the sector, favorable geographic position and climatic conditions, and rich biodiversity. Therefore, there is great potential to utilize waste resulting from the processing of this culture, especially sugarcane bagasse, a byproduct arising from the extraction of its juice by grinding (Vieira et al., 2012). However, this process also contributes to increased waste in landfills.

A viable solution to this problem would be to use thermal energy that could be derived from these residues (sugarcane bagasse) through combustion. Nonetheless, such biomass is usually not suitable for direct combustion, and techniques to enable its use and amplify its energy efficiency are needed, such as thermomechanical or densification treatments in the form of briquettes or pellets.

Pelletization involves of crushing and compacting waste under high pressure and temperature (Chin & Siddiqui, 1999). Pelletized biomass has a greater energy density and higher calorific power, besides being more suitable for transport and storage (Furtado et al., 2010; Hogland et al., 1994), in addition to the ability to emit less CO_2 due to neutrality in the carbon balance (Garcia et al., 2017). Adding fatty binders (glycerol, pyroligneous oil and black liquor) to the mixture may benefit the compaction process, yielding physical and energetic improvements (Tumuluru et al., 2011).

In this context, studies that aim to elucidate the thermal behavior of alternative energies produced from biomasses become important, including those examining the feasibility of alternative processes for the use of these energy resources in industries. This would contribute directly to improve economic activity and to decrease solid waste accumulation in landfills.

In view of the above, and to validate the use of waste from sugarcane bagasse processing for energy purposes, this study aimed to carry out a chemical and physical analysis of the combustion process of pellets made from sugarcane bagasse with and without the addition of glycerol as a particle binder.

2. Materials and Methods

2.1 Pellet Production Process

The processes involved in the production of sugarcane bagasse pellets (SBP100) and 70% sugarcane bagasse with 30% glycerol pellets (SBP30G) can be seen in Figure 1. Due to its moisture content of approximately 85% (Furtado et al., 2010) after collection in its natural state, the bagasse was sliced in pieces and subjected to a drying process by sunlight exposure during 72 hours (Figure 1A). Drying this biomass is important to provide improved densification and subsequent combustion of the pellets.

The biomass was then crushed in an electric forage grinder (Trf400f 2cv - Trapp) to obtain sugarcane bagasse powder (Figure 1B). The powder then underwent heat treatment at approximately 80 °C for 20 minutes in a thermal oven, in order to protect pellets from phytopathogenic organisms (Figure 1C).

Only sugarcane bagasse powder (SBP100), or sugarcane bagasse powder (70%) with glycerol (30%) were used in the production of pellets (Figure 1D), the powders were distributed in cylinders (20 cm x 8 mm) and maintained under 570 bar pressure (via a hydraulic actuator) for 15 minutes in a manual pelletizer (Figure 1E). The pellets were then removed from the cylinders and divided into approximately 2 cm-long pieces (Figure 1F).

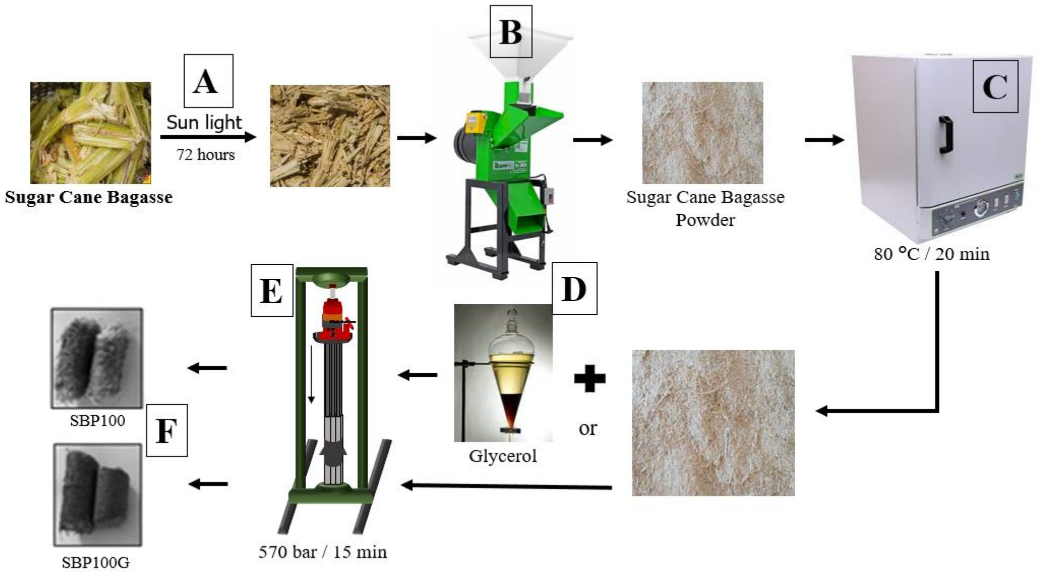

Figure 1. Pellet Production Process. A-Drying Process; B-Bioma Crushing; C-Heat Treatment; D-Manual Pelletizer; E- SBP100 and SBP30G pellets

2.2 Chemical Analysis

The immediate aim of the chemical analyses was to assess moisture $(\%U)$, volatile materials $(\%V)$, ash $(\%C)$ and fixed carbon $(\%;FC)$ present in the biomasses, for energy purposes (Garcia et al. 2016). In summary, three samples of 1.00±0.05 g of each type of pellet (CSP and CNSP) were placed in a crucible and weighed on an analytical balance, and immediately heated in a thermal oven at 105°C for 4 hours and then cooled in a desiccator until room temperature, before being weighed again.

To determine the variables of immediate chemical analysis, the following standards were used: ASTM E871-82 for moisture content ($\%U$); ASTM E872-82 for volatile matter content $(\%V)$; and ASTM D1102-84 for ash content $(\%C)$. Finally, the determination of fixed carbon content $(\%FC)$ was performed according to equation 1 (ASTM D-1762/64):

$$\%FC = 100 - (\%U + \%V + \%C) \quad (1)$$

In order to determine sample (CSP or CNSP) density ( ), pellets were initially weighed ( ), and their respective volumes ( ) were calculated.

2.3 Combustion Metal Furnace (CMF) and Combustion Tests

To carry out SBP100 or SBP30G combustion tests, a combustion metal furnace was built (CMF - Figure 2). Tests were performed in triplicate, lasting 1 hour each and using 100 g of biomass per test. For each combustion test, initial ignition occurred using natural gas (Figure 2A - 5 L/min), with oxygen provided by an air compressor (Figure 2B - 3 L/min). The initial ignition lasted approximately 30 seconds, and the natural gas supply was shut off immediately afterward, leaving only the compressor's air supply during the entire combustion process (1 hour).

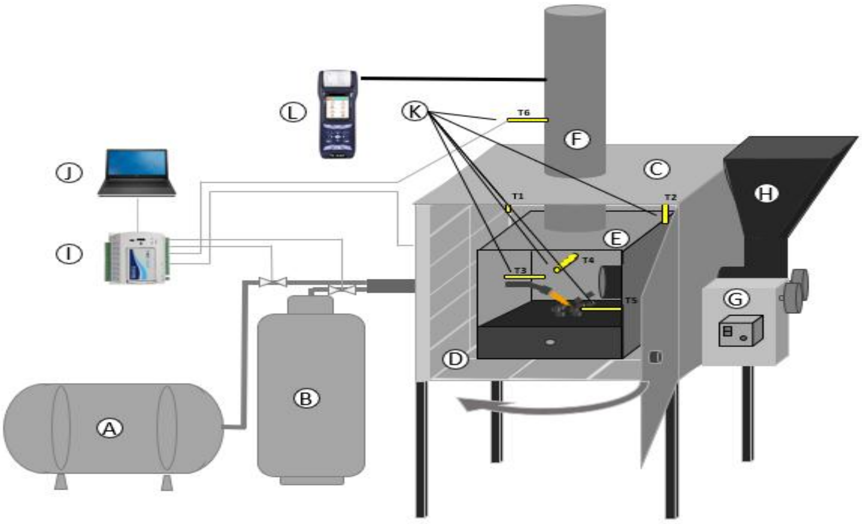

Figure 2 - Combustion testing platform. A- Air compressor; B- Natural gas cylinder; C- Combustion Metal Furnace; D- Internal thermal insulation; E- Internal combustion chamber; F- Chimney; G- Engine; H- Storage silo; I- Datalogger; J- Notebook; K- Thermocouples; L- Gas analyzer

The CMF had an external stainless-steel casing (Figure 2C - 90 cm high, 47.5 cm wide and 46 cm long) and internal thermal insulation using bricks (Figure 2D - composition: 30/35% Al_2O_3; 60/64% SiO_2; 2% Fe_2O_3). The CMF also contained a stainless-steel internal combustion chamber (Figure 2E - 20 cm high, 30 cm wide, 30 cm long), with a chimney for gas exhaustion (Figure 2F - 25 cm high and 8 cm diameter). The SBP100 or SBP30G pellets were fed continuously into the chamber throughout the 1-hour test period, by means of a motor coupled to a worm screw (Figure 2G) and a pellet storage silo (Figure 2H).

All gas flow and temperatures arising during the combustion process were monitored using a data logger (Figure 2I - Fieldlogger®) and a notebook computer (Figure 2J). Monitoring was achieved using five thermocouples (Figure 2K), two of which were placed inside the CMF (T1 and T2), two inside the combustion chamber (T3 and T4), and one in the CMF chimney (T5). Combustion exhaust gas was evaluated using a gas analyzer (Seintro Chemist 900 by Ecil®) during the entire process (Figure 2L).

3. Results

Table 1 shows results regarding moisture content and density analyses, as well as the immediate chemical analyses performed on SBP100 and SBP30G. For moisture content (%U), values of 12.77±0.36% and 9.91±1.40% were obtained for SBP100 and SBP30G, respectively. Densities of 845.25± 23.99 kg/m³ and 785±34.75 kg/m³ were obtained for SBP100 and SBP30G, respectively. For volatile materials content ($\%V$), values of 79,70±2.23% and 87.94±1.57% were obtained for SBP100 and SBP30G, respectively. Ash content ($\%C$) values of 0.3±0.05% and 0.86±0.09% were determined for SBP100 and SBP30G, respectively. Fixed carbon ($\%FC$) values of 20.00±2.28% and 11.75±1.08% were found for SBP100 and SBP30G, respectively.

Table 1. Immediate Chemical Analysis

Biomass	SBP100			SBP30G		
	Mean±SD	Max	Min	Mean±SD	Max	Min
Moisture ($\%U$)	12.77±0.36	14.19	11.68	9.91±1.40	10.87	9.55
Density (kg/m³)	845.25±23.99	851.29	843.75	785±34.75	807.25	768.36
Volatile Materials ($\%V$)	79.70±2.23	81.39	77.16	87.94±1.57	89.32	86.23
Ashes ($\%C$)	0.31±0.05	0.34	0.24	0.86±0.09	0.93	0.76
Fixed Carbon ($\%FC$)	20.00±2.28	22.59	18.29	11.75±1.08	12.83	10.68

Figure 3 shows the temporal profile of temperatures for the five thermocouples distributed inside the CMF. Table 2 shows the average, maximum and minimum temperatures for the thermocouples. Values seen at T3 represent the temperatures in the exact region where combustion took place. Mean values found at T3 were 213.62±137.07° C and 211.97±86.85° C for SBP100 and SBP30G combustion, respectively. Maximum values at T3 were 709.37º C and 469.55° C, and a minimum of 35.10° C and 96.83° C were observed during SBP100 and SBP30G combustion, respectively.

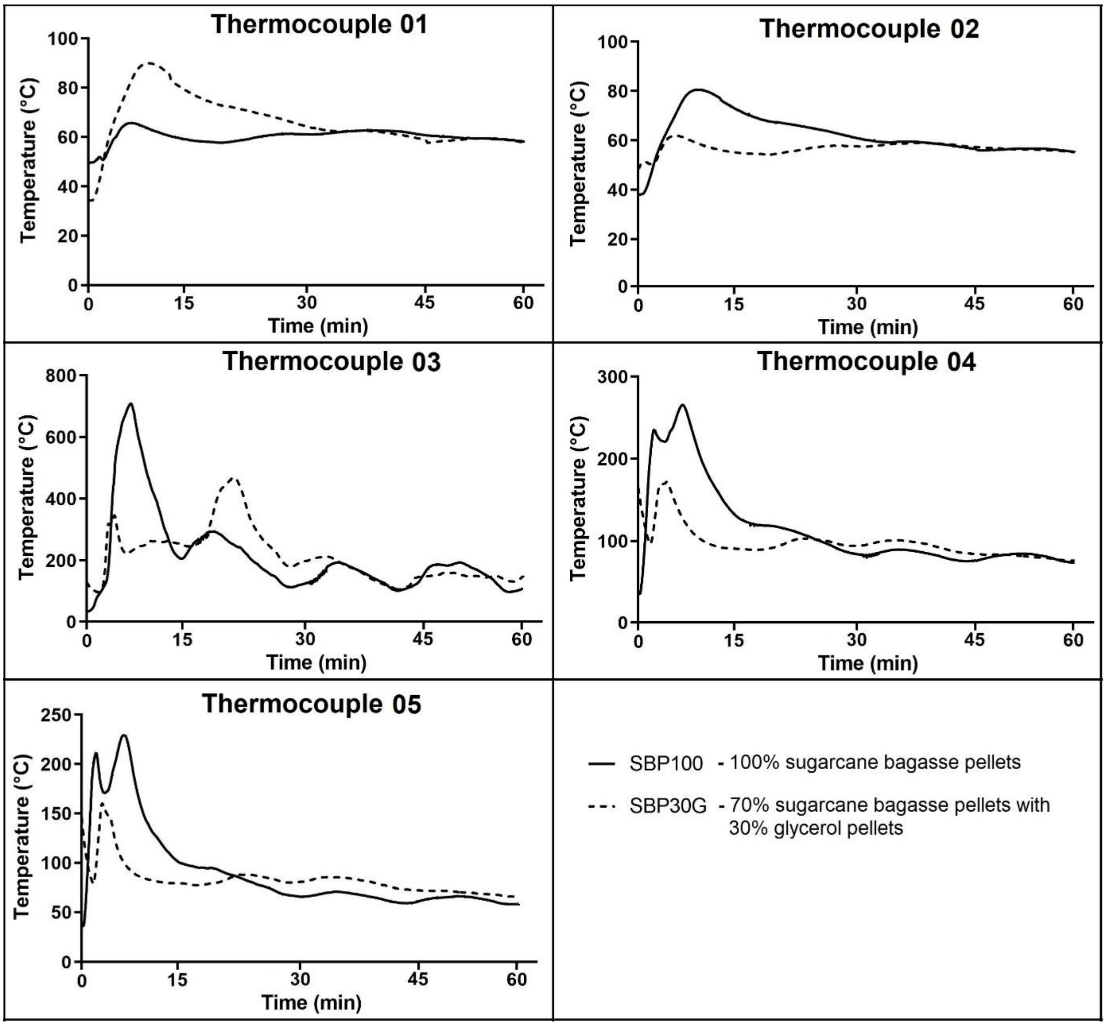

Figure 3. Temporal Temperature Analysis in Combustion Metal Furnace (CMF) during the Combustion Tests of SBP100 and SBP30G

Also in Table 2, T5 values represent exhaust gas temperatures. Average values at T5 were 90.16±43.13° C and 82.82±15.95° C for SBP100 and SBP30G combustion, respectively. Maximum temperatures of 229.43° C and 157.85º C were observed at this point, and minimum values of 35.93° C and 65.93º C were seen for SBP100 and SBP30G, respectively.

Table 2. Temperature Profile in the Combustion Metal Furnace (CMF)

Thermocouples	Temperature (Mean - °C)		Temperature (Max - °C)		Temperature (Min - °C)	
	SBP100	SBP30G	SBP100	SBP30G	SBP100	SBP30G
T1	66.38±10.51	60.30±2.74	90.00	65.76	34.37	48.96
T2	62.41±8.23	56.94±2.13	80.60	61.96	38.07	48.46
T3	213.62±137.07	211.97±86.85	709.37	469.55	35.10	96.83
T4	113.85±51.05	97.48±18.76	265.77	172.35	35.70	76.43
T5	90.16±43.13	82.82±15.95	229.43	159.85	35.93	65.93

Table 3 shows the mean values for O_2 percentage and CO, NOx and CH_4 concentrations in exhaust gases derived from SBP100 and SBP30G combustion. Figure 4 shows the mean values for O_2 percentage and CO, NO_x and CH_4 concentrations of the exhaust gases for both pellet types. Values of 20.04±0.15% and 19.95±0.19% of O_2 were found in SBP100 and SBP30G exhaust gases, respectively.

Table 3. Mean Values of the Exhaust Gases from the Combustion of SBP100 and SBP30G

Exhaust Gases	Biomass	
	SBP100	SBP30G
O_2 (%)	20.04±0.15	19.95±0.19
CO (ppm)	1739.58±156.17	1575±466.85
NO_x (ppm)	19.92±2.47	17.33±4.69
CH_4 (ppm)	341.67±134.37	491.67±341.42

CO levels of 1739.58±156.17 ppm and 1575±466.85 ppm was found in the exhausts of SBP100 and SBP30G, respectively. Values of 19.92±2.47 ppm and 17.33±4.69 ppm were found for NO_x concentration in the gases from SBP100 and SBP30G combustion, respectively. As for CH_4 concentration, values of 341.67±13 4.37 ppm and 491.67±341.42 ppm were observed for SBP100 and SBP30G, respectively.

Figure 4 displays the temporal analysis of O2, CO, NO, and CH4 concentrations over the 60 minutes of the testes.

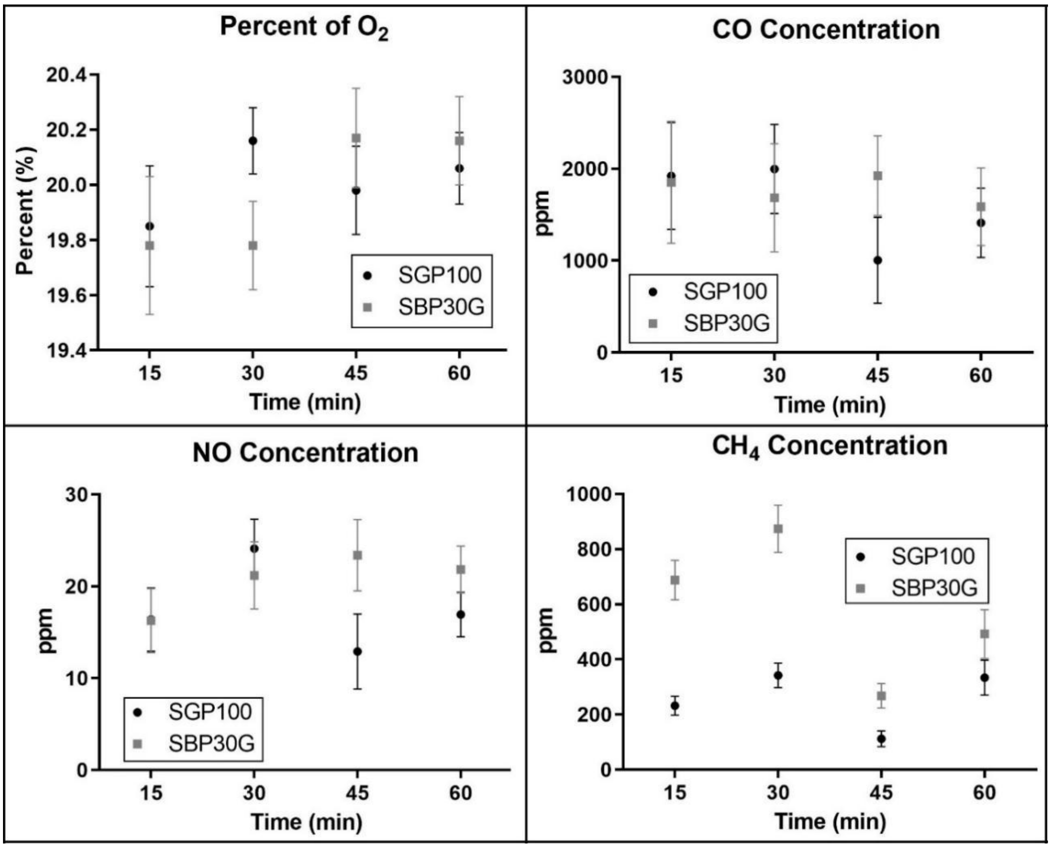

Figure 4. Temporal Analysis of the Percentage of O_2 and Concentration of Pollutants Present in Exhaust Gases from the Combustion of SBP100 and SBP30G

4. Discussion

Alternative energy sources have become a preferred choice over fossil and non-renewable fuels. Among these alternative substrates, biomass stands out due to current environmental and public health demands. This scenario yields significant interest in the use of such residues arising from subsistence agriculture, particularly in small rural communities that depend on the cultivation of such crops as main income.

With this perspective, the present work aimed to analyze the chemical and thermal characteristics of SBP100 and SBP30G combustion. This study aimed to use low-cost materials throughout the ~~entire~~ production process of the SBP100 and SBP30G, thus using substances that could be easily purchased by small communities.

4.1 Chemical Analyses

Table 1 presents the average moisture content percentage (%U) values for SBP100 and SBP30G, respectively, over the 120-minute drying period in an oven at 105º C. All moisture values for our biomass showed a progressive reduction over the two-hour period.

We found mean values of 12.77±0.36% for SBP100 and 9.91±1.40% for SBP30G. SBP100 had a higher average moisture, compared to SBP30G. Moisture content (%U) exerts direct influence on the calorific capacity of biomass and, consequently, of the resulting pellets. Our values are lower when compared to values found in previous the literature, such as those for eucalyptus sawdust pellets (15%) (Protásio et al., 2015), and green coconut shell pellets (16-17%) (Santos et al., 2022).

Remarkably, SBP30G should have a higher moisture content when compared to other pellets due to the humectant property of glycerol. However, studies claim that glycerin tends to lose its humectant roperty when exposed to temperatures above 200° C for longer than 60 minutes (Galy et al., 2017).

Biomass combustion reactions use a maximum humidity limit of approximately 65%. For values higher than this, the substrate would consume a greater amount of energy to be able to react, thus rendering the process inefficient, as the moisture present would require higher levels of heat in order to simply evaporate (Jenkins et al., 1998).

Agricultural biomass with moisture values above 23% may present high quantities of phytopathogenic microorganisms that would degrade the organic matter in the pellets, thus affecting their quality. In addition, this would present health risks to those who are required to manipulate the materials for production of the pellets (Mani et al., 2006).

Regarding the mean density values, we obtained 845.25±23.99kg/m³ and 785±34.75 kg/m³, respectively, for SBP100 and SBP30G (Table 1). The higher density value for SBP100, when compared to SBP30G, indicates that SBP100 has greater compression potential than SBP30G. Some studies suggest explanations for the resulting SBP30G density.

Sugarcane bagasse is a lignocellulosic biomass, which makes it susceptible to the influence of other viscous adjuvant substances, such as glycerol (Bartocci et al., 2018; Marrugo et al., 2019). This chemical tends to degrade and disorganize lignin and cellulose structures when used in the pre-treatment of lignocellulosic biomass, lowering its crystallinity and increasing the surface area of the material (Elis et al., 2010; Mani & Sokhansanj, 2003), causing an increment in its specific volume and influencing its absolute and apparent density.

The energy efficiency of pellet samples was also assessed through their Higher Heating Value (HHV). The SBP100 sample exhibited an HHV of approximately 14.34 MJ/kg, while the SBP30G sample recorded an HHV of 14.84 MJ/kg. The observed difference in sample values suggests that variations in composition or manufacturing processes had implications for their heating value. Similar results were reported for percentages of 20% and 40% glycerol as a binder in the composition of sugarcane bagasse pellets (Marrugo et al., 2019).

The lignin-degrading property of glycerol is possibly related to SBP30G's absolute density reduction, when compared to SBP100. Pellet density is a direct product of their energy density (Zhang et al., 2016). Additionally, pellet density may determine the amount of mass that can be transported or stored in a fixed-volume container. Density values found in our study are higher for both pellets, when compared to the Brazilian standard ISO 17828 for wood pellets (600-750 kg/m³).

According to (ABNT/NBR17030, 2022), pellets of any kind with a density greater than 650 kg/m³ facilitate and improve storage and transport operations, especially over longer distances. Our values for both pellets were higher than 650kg/m^3. (Liu et al., 2013) observed mean density values of 1,250 kg/m^3 and 1,350 kg/m^3 for pellets produced with bamboo particles and rice husks, respectively. However, the authors did not report the pressures used during pellet manufacturing, and this parameter directly influences density.

Mean values of 79.70±2.23% and 87.94±1.57% of volatile content were found, respectively, for SBP100 and SBP30G (Table 1). SBP30G presented the highest volatile content values (89.32%), while SBP100 presented the lowest (81.39%). The addition of glycerol during the manufacture of pellets promoted increased values of volatile materials for the studied biomass.

Volatile matter amount (%V) represents the fuel behavior during thermal decomposition. All values found for SBP30G and SBP100 are, respectively, similar to those from previous works: 83.45% to 84.98% for wood pellets (Garcia et al., 2016) and 88.09±0.85% for chestnut shell pellets (Santos et al., 2022). Based on these values, we observed that SBP30G must present a lower ignition temperature, since higher levels of volatile materials and fast emissions are factors that contribute decisively to accelerate fuel ignition at a lower temperature (Moon et al., 2013).

Regarding ash content, we found values of 0.31±0.05% for SBP100 and 0.86±0.09% for SBP30G (Table 1). Ash content represents the percentage of mineral components contained in the biomass, which may be a consequence of aggregation during plant growth or external factors such as handling and harvesting processes (Brand, 2007).

All mean values found for the pellets in our analyses were lower than those of results found in previous studies evaluating the ash content of pine bark pellets (3.45% to 3.71%) (Lethikangas, 2001), sorghum biomass pellets (4.01%) Lúcia et al., 2018), and elephant grass pellets (10.9%) (Magalhões et al., 2016).

In general, ash content levels lower than 1% have little influence on the pellet densification process. However, values lower than 10% may negatively interfere with the pelleting equipment lifespan EPE 2018). Although Brazil does not have a consolidated standard for this parameter, we can use the DNI 51731 standard (DEUSTSCHES INSTITUT FUR NORMUNG 1996), which determines that granules must contain a maximum of 1.5% of ash in their chemical composition, regardless of their class. All our results are in line with this standard.

As for the influence of glycerol on the SBP30G ash content behavior, previous works have already shown a similar correlation. (Shi et al., 2019) observed a reduction followed by an increase in the ash content for sugarcane bagasse with glycerol when heat-treated at temperatures of 130º C, 170º C and 210º C.

For the fixed carbon content ($\%FC$), values of 20.00±2.28% for SBP100 and 11.75±1.08% for SBP30G were observed. Our findings are similar to those from previous works showing approximate values of 15% for wood pellets (Garcia et al., 2016), 9% for sorghum biomass pellets (Lúcia et al., 2018), and 19-22% for pellets from apple and pine tree cuttings (Brand & Jacinto, 2020).

Fixed carbon content affects the burning process inside the combustion chamber, with higher values leading to slower burning, greater thermal stability, and lower ignition temperatures (Moon et al., 2013). Fixed carbon has an indirect relationship with volatile materials (%V). If we define the carbonization index (CI) as an indirect way of relating volatile materials and fixed carbon, being as the direct ratio between these values respectively ($\%V/\%FC$), a higher value of this index indicates that a significant amount of volatiles is released in relation to the fixed carbon present in biomass. This may suggest a greater tendency for the release of gases during heating processes, such as combustion or pyrolysis. In this case, taking the average values presented in Table 1, we will notice that the SBP30G (CI = 7.484) will tend to release more gases than the SBP100 (CI = 3.540).

4.2 Thermal Analysis of the Combustion Process

Thermal analyses of the combustion process of SBP100 and SBP30G can be seen in Table 2 and Figure 3. Results found in T1 and T2 represent the CMF's thermal insulation efficiency. We observed similar mean values in these thermocouples (Table 2), indicating homogeneity in the oven's interior temperature. T3 and T4 show the temperature inside the internal combustion chamber (Figure 2E), with no significant variations observed between the mean combustion values for SBP100 and SBP30G at T3 (Table 2).

The average temperatures obtained during SBP100 and SBP30G combustion are apparently similar, except for the temperatures at T4 and T5 (Table 2 – Figure 3). T3 detects the temperatures in the exact combustion range and T5 shows combustion exhaust gas temperatures. Temperature values in T3 were higher for SBP100, when compared to SBP30G, leading us to expect higher values in T5 for SBP100, when compared to SBP30G, considering the higher the combustion temperature reached (T3), the higher the temperature of the combustion gases (T5).

However, we found lower mean temperature values at T3 and T5 for SBP30G combustion when compared to SBP100, which can be explained by the higher content of volatile materials ($\%V$) in SBP30G (Table 1). Greater volatile content may be related to the rapid thermal decomposition, which can yield faster combustion and higher temperatures in the emission gases.

During combustion tests, peak temperatures found in T3 (combustion range) were 709.37° C for SBP100 and 469.55 °C for SBP30G. A previous study analyzed the carbonization of *Eucalyptus urophylla* and *cloeziana* and found peak temperatures for the decomposition of cellulose, hemicelluloses and lignin at 360°C, 310°C and 430°C, respectively (Raad et al., 2006), demonstrating that the maximum temperature reached during our combustion tests is sufficient for thermal decomposition of these materials (Henrique et al., 2015).

4.3 Analysis of Exhaust Gases from the Process of Combustion

The analyses of the combustion exhaust gases can be seen in Table 3 and Figure 4. In general, CO and NO_x concentrations were lower for SBP30G, when compared to SBP100, throughout the 1-hour burning process, while an inverse behavior was observed in the concentrations of CH_4 for these pellets (Table 3 and Figure 4). Regarding O_2 percentage, no significant differences were observed between the mean values (Table 3). We also observed values that changed over time when comparing SBP100 and

SBP30G combustion (Figure 4 – Percent of O_2). The drop in oxygen values in the exhaust gases of SBP100 and SBP30G, in relation to the ambient percentage (21%), was expected, due to use of this gas during the burning process.

Regarding CO concentration, lower mean values were observed in the exhaust of SBP30G in comparison to SBP100 (Table 3 and Figure 4 - CO Concentration). These results can be explained by the fact that SBP30G displayed lower temperatures in the combustion range (Table 2 – T3), which implies a high CO concentration. All pellets (SBP100 and SBP30G) surpassed the value of 2000 ppm of CO in the flue gases at some point during the tests. According to the World Health Organization, chronic exposure to small concentrations of CO can generate harmful health effects, such as hypoxia and endothelial inflammation (WHO 2010).

NO_x mean values in the exhaust gases from SBP100 combustion were higher when compared to SBP30G values (Table 3), a phenomenon also observed in the temporal analyses (Figure 4 – NO_x Concentration). Regarding exposure to NO_x, the nitrogen monoxide (NO) oxidation processes can lead to formation of nitrogen dioxide (NO_2), a pollutant known for causing several respiratory diseases (Castro et al., 2013).

Mean CH_4 concentrations in the exhaust arising from SBP30G combustion were much higher than those found for SBP100 (Table 3 and Figure 4 – CH_4 Concentration). CH_4 is an intermediate compound in the conversion of the fixed carbon content ($\%FC$) of SBP100 and SBP30G to CO_2. Low burning temperatures promote increased CH_4 in the flue gases. This may explain the higher CH_4 values found for SBP30G, since the combustion of these pellets displayed lower average temperatures (Table 2 – T3). Large methane concentrations in the exhaust indicate lower fuel efficiency during the conversion of carbon to CO_2, which may be related to the higher CO concentrations in the exhaust from SBP30G (Table 3). Another possible reason for the increased CH_4 concentrations for SBP30G, when compared to SBP100, would be the presence of glycerol, as this substance, when present in biomass, is capable of generating methane during heating processes and anaerobic digestion (Reis, 2020).

5. Conclusion

In conclusion, combustion of pellets in ovens can be an efficient way to use solid and liquid residues, as they have higher thermal efficiency when compared to the combustion of raw biomass. The densification of biomass in the form of pellets with binders can be an attractive economic and social solution for the reuse of such residues. SBP30G combustion processes proved to be less polluting in terms of CO and NO_x generation than SBP100, but not for CH_4. Overall, both pellet types showed similar average thermal performances. The use of glycerol contributed considerably to changes in the physical parameters of sugarcane bagasse pellets. The analyses of exhaust gases arising from the biomass used in this work may influence the improvement of legislation regarding the combustion of sugarcane derivatives, as well as promote the creation of safety parameters and public policies for regulating the use of biomass for energy purposes.

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References

ABNT. (2022). *Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards) NBR 17030 – Pellets – Terminologia e método de ensaios*. Rio de Janeiro: ABNT.

ABNT. (2022). *Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards) NBR 17013 – Pellets – Requisitos e classificação – Parte 1: Madeira de Pinus*. Rio de Janeiro: ABNT.

Bartocci, P., Bidini, G., Asdrubali, F., Beatrice, C., Frusteri, F., & Fantozzi, F. (2018). Batch pyrolysis of pellet made of biomass and crude glycerol: Mass and energy balances. *Renewable Energy*, *124*, 172-179. https://doi.org/10.1016/j.renene.2017.06.049

Biomassa, D. E., & Florestais, A. E. (2020). *PRODUÇÃO DE PELLETS PARA ENERGIA USANDO DIFERENTES RESÍDUOS*.

Brand, M. A. (2007). *Quality of forest biomass for use in power generation due to storage* (PhD Thesis). Federal University of Paraná, Brazil.

Brand, M. A., & Jacinto, R. C. (2020). Apple pruning residues: Potential for burning in boiler systems and pellet production. *Renewable Energy*, *152*, 458-466. https://doi.org/10.1016/j.renene.2020.01.037.

Castro, A. H. S., Araujo, R. S., & Silva, G. M. M. (2013). Air quality – Control parameters and effects on human health: A brief review. *Holos*, *5*, 107-121. https://doi.org/10.15628/holos.2013.1242

Chin, O. C., & Siddiqui, K. M. (n.d.). *Characteristics of some biomass briquettes prepared under modest die pressures*. Retrieved from http://www.elsevier.com/locate/biombioe

Deustsches Institut Fur Normung. (1996). *DIN 51731: Testing of Solid Fuels: Compressed Untreated Wood, Requirements and Testing*. Berlin: Deustsches Institut Fur Normung.

DNI - Deustsches Institut Fur Normung. (1996). *DNI 51731/1996-10 - Testing of solid fuels - Compressed untreated wood - Requirements and testing*. Berlin: GNS.

Dos Santos, G. R., de Sousa, A. M., Lima, B. K. S., Moreira, F. L., Gondim, F. L., da Silva, G. M., Ratts, M. G. A. C., Serra, D. S., de Oliveira, M. L. M., & Cavalcante, F. S. Á. (2022). Combustion of pellets produced from the powders of coconut and cashew nut shells: Chemical, thermal and emission analyses. *Waste Management and Research*, *40*(4), 420-428. https://doi.org/10.1177/0734242X20983417

Elis, L., Ramos, D. E., & Paula, E. (2010). *PRODUÇÃO E AVALIAÇÃO DE BRIQUETES DE RESÍDUOS LIGNOCELULÓSICOS*.

EPE, Empresa de Pesquisa Energética (Energy Research Company). (2018). Matriz Energética e Elétrica (Energy and electrical matrix). Retreived from https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balancoenergetico-nacional-2018

Furtado, T. S., Valin, M., Brand, M. A., & Bellote, A. F. J. (2010). Variáveis do processo de briquetagem e qualidade de briquetes de biomassa florestal. *Pesquisa Florestal Brasileira*, *30*(62), 101-106. https://doi.org/10.4336/2010.pfb.30.62.101

Galy, N., Nguyen, R., Yalgin, H., Thiebault, N., Luart, D., & Len, C. (2017). Glycerol in subcritical and supercritical solvents. *Em Journal of Chemical Technology and Biotechnology* (Vol. 92, Número 1, p. 14-26). https://doi.org/10.1002/jctb.5101

Garcia, D. P. (2010). *Chemical, physical and thermal characterization of wood pellets produced in Brazil* (PhD Thesis). Paulista State University, Brazil.

Garcia, D. P., Caraschi, J. C., & Ventorim, G. (2016). DECOMPOSIÇÃO TÉRMICA DE PELLETS DE MADEIRA POR TGA. *HOLOS*, *1*, 327-339. https://doi.org/10.15628/holos.2016.3886

Garcia, D. P., Caraschi, J. C., & Ventorim, G. (2017). Emissões de gases do efeito estufa da queima de pellets de madeira (Greenhouse gas emissions from burning wood pellets). *Floresta*, *47*, 297-306. https://doi.org/10.5380/rf.v47i3.50952

Garcia, D. P., Caraschi, J. C., & Ventorim, G. (2017). O setor de pellets de madeira no Brasil. *Revista Ciência da Madeira - RCM*, *8*(1), 21-28. https://doi.org/10.12953/2177-6830/rcm.v8n1p21-28

Garcia, D. P., Caraschi, J. C., Dal Bem, E. A., Ferreira, J. P., Souza, F. M. L., Vieira, F. H. A., & Dias, R. R. (2018). MAPA DOS PRODUTORES BRASILEIROS DE BIOCOMBUSTÍVEIS PELLETS. In *Brazilian Journal of Biosystems Engineering v* (Vol. 12, Número 4). https://doi.org/10.18011/bioeng2018v12n4p333-339

Henrique, M. A., Flauzino Neto, W. P., Silvério, H. A., Martins, D. F., Gurgel, L. V. A., Barud, H. da S., Morais, L. C. de, & Pasquini, D. (2015). Kinetic study of the thermal decomposition of cellulose nanocrystals with different polymorphs, cellulose I and II, extracted from different sources and using different types of acids. *Industrial Crops and Products*, *76*, 128-140. https://doi.org/10.1016/j.indcrop.2015.06.048

Hogland, W., Bramryd, T., & Persson, I. (n.d.). *PHYSICAL, BIOLOGICAL AND CHEMICAL EFFECTS OF UNSORTED FRACTIONS OF INDUSTRIAL SOLID WASTE IN WASTE FUEL STORAGE Sölvegatan*, *3*, S-223, 62.

Jenkins, B. M., Baxter, L. L., & Miles, T. R. (1998). Combustion properties of biomass. *Fuel Processing Technology* (Vol. 54, pp. 17-46). https://doi.org/10.1016/S0378-3820(97)00059-3

Lehtikangas, P. (2001). Quality properties of pelletised sawdust, logging residues and bark. B*iomass and Bioenergy*, 20, 351-360. https://doi.org/10.1016/S0961-9534(00)00092-1

Liu, Z., Fei, B., Jiang, Z. et al. (2013). The properties of pellets from mixing bamboo and rice straw. *Renewable Energy*, *55*, 1-5. https://doi.org/10.1016/j.renene.2012.12.014

Lúcia, M., Simeone, F., Augusto Da Costa Parrella, R., May, A., Robert, & Schaffert, E. (2018). *PRODUÇÃO E CARACTERIZAÇÃO DE PELLETS DE SORGO BIOMASSA*.

Magalhões, M. A. de, Donato, D. B., Canal, W. D., Carneiro, A. de C. O., Pereira, B. L. C., & Vital, B. R. (2016). Caracterização de pellets produzidos a partir de capim-elefante para uso energético. *Revista Ciência da Madeira - RCM*, *7*(3), 155-162. https://doi.org/10.12953/2177-6830/rcm.v7n3p155-162

Mani, S., & Sokhansanj, S. (2003). Preprocessing and Characterization of lignocellulosic biomass View project Biomass Size Reduction View project. Retrieved from https://www.researchgate.net/publication/230704670

Mani, S., Tabil, L. G., & Sokhansanj, S. (2006). Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass and Bioenergy*, *30*(7), 648-654. https://doi.org/10.1016/j.biombioe.2005.01.004

Marrugo, G., Valdés, C. F., Gómez, C., & Chejne, F. (2019). Pelletizing of Colombian agro-industrial biomasses with crude glycerol. *Renewable Energy*, *134*, 558-568. https://doi.org/10.1016/j.renene.2018.11.004

Moon, C., Sung, Y., Ahn, S. et al. (2013). Effect of blending ratio on combustion performance in blends of biomass and coals of different ranks. *Experimental Thermal and Fluid Science*, *47*, 232-240. https://doi.org/10.1016/j.expthermflusci.2013.01.019

Protásio, T. D. P., Trugilho, P. F., De Siqueira, H. F., De Melo, I. C. N. A., Andrade, C. R., & Guimarães Junior, J. B. (2015). Caracterização energética de pellets in natura e torrificados produzidos com madeira residual de Pinus. *Pesquisa Florestal Brasileira*, *35*(84), 435. https://doi.org/10.4336/2015.pfb.35.84.843

Quirino, W. F., Teixeira Do Vale, A., Ana, Abreu De Andrade, P., Lúcia, V., Abreu, S., Cristina, A., & Azevedo, S. (n.d.). *PODER CALORÍFICO DA MADEIRA E DE MATERIAIS LIGNO-CELULÓSICOS Publicado na Revista da Madeira nº 89 abril 2005 pag 100-106.*

Raad, T. J., César, P., Pinheiro, C., & Yoshida, M. I. (2006). *EQUAÇÃO GERAL DE MECANISMOS CINÉTICOS DA CARBONIZAÇÃO DO Eucalyptus spp* (Vol. 12, Número 2, p. 100-106).

Reis Queiroz, C. G. (2020). *PRODUÇÃO DE BIOGÁS POR DIGESTÃO ANAERÓBIA DE GLICEROL BRUTO.*

Shi, T., Lin, J., Li, J., Zhang, Y., Jiang, C., Lv, X., Fan, Z., Xiao, W., Xu, Y., & Liu, Z. (2019). Pre-treatment of sugarcane bagasse with aqueous ammonia–glycerol mixtures to enhance enzymatic saccharification and recovery of ammonia. *Bioresource Technology*, *289*. https://doi.org/10.1016/j.biortech.2019.121628

Tumuluru, J. S., Wright, C. T., Hess, J. R., & Kenney, K. L. (2011). A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels, Bioproducts and Biorefining* (Vol. 5, Número 6, pp. 683-707). https://doi.org/10.1002/bbb.324

Vieira, M. A., Formaggio, A. R., Rennó, C. D., Atzberger, C., Aguiar, D. A., & Mello, M. P. (2012). Object Based Image Analysis and Data Mining applied to a remotely sensed Landsat time-series to map sugarcane over large areas. *Remote Sensing of Environment*, *123*, 553-562. https://doi.org/10.1016/j.rse.2012.04.011

World Health Organization (WHO). (2010). *World Health Organization Guidelines for Indoor Air Quality: Selected Pollutants*. Copenhagen, Denmark: WHO Regional Office for Europe.

Zanetti, J. B., Fiusa, R., Bruno, M., Rodrigues, J., Robert, A., Boddey, M., Urquiaga, S., Henrique, L., & Soares, B. (2010). *Boletim de Pesquisa e Desenvolvimento 71 Balanço de energia na produção de capim-elefante em condições experimentais Embrapa Agrobiologia Seropédica, RJ 2010 Empresa Brasileira de Pesquisa Agropecuária Embrapa Agrobiologia Ministério da Agricultura, Pecuária e Abastecimento*. Retrieved from http://www.cnpab.embrapa.br

Zhang, Q., Zhang, P., Pei, Z. et al. (2016). Ultrasonic vibration-assisted pelleting of cellulosic biomass for ethanol manufacturing: An investigation on pelleting temperature. *Renewable Energy*, *86*, 895-908. https://doi.org/10.1016/j.renene.2015.08.043