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Articles

Energy characterization of agricultural and forestry biomasses in the state of Pernambuco

Caracterização energética de biomassas agrícolas e florestais no estado de Pernambuco

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ABSTRACT

The search for sustainable and less polluting alternatives has intensified, such as the use of biomass residues for energy purposes, replacing fossil fuels and derivatives. The objective of this study was to evaluate the energy potential of agricultural and forestry biomasses for energy generation, as well as to, determine their physical, chemical and energetic properties. To carry out this analysis five agricultural and forestry biomasses from productive processes in the state of Pernambuco were used, namely: sugarcane bagasse, eucalyptus bark, eucalyptus chips, wood sawdust and pruning of urban trees in the municipality of Recife. Sugarcane bagasse (18,405 KJ/Kg), followed by sawdust (18,115 KJ/Kg), and eucalyptus chips (18,024 KJ/Kg), had the highest calorific value. As for elemental chemistry, the hydrogen content was the only one that did not show a significant difference between the biomasses, and the sugarcane bagasse presented the best values of oxygen and sulfur, in addition to high carbon content. Regarding energy density and IVC, eucalyptus chips (6.16 GJ/m³ and 307, respectively), and sawdust (5.91 GJ/m³ and 32, 86, respectively), presented the highest values. All evaluated biomasses have energy potential, however, based on the variables, sugarcane bagasse, sawdust and eucalyptus chips, tend to have greater combustibility.

Keywords: Residues; Renewable source; Bioenergy; Organic matter; Energy sources

RESUMO

Tem se intensificado a busca por alternativas sustentáveis e menos poluentes, como o aproveitamento de resíduos de biomassa para fins energéticos, substituindo os combustíveis fósseis e derivados. O objetivo deste estudo foi avaliar o potencial energético de biomassas agrícolas e florestais para geração de energia. Além disso, determinar suas propriedades físicas, químicas e energéticas. Para realizar esta análise, utilizou-se cinco biomassas agrícolas e florestais de processos produtivos no estado de Pernambuco, são elas: bagaço de cana-de-açúcar, casca de eucalipto, cavaco de eucalipto, serragem de madeira e poda da arborização urbana do município de Recife. O bagaço de cana-de-açúcar (18.405 KJ/Kg), seguido pela serragem (18.115 KJ/Kg) e cavaco de eucalipto (18.024 KJ/Kg), obtiveram maior poder calorífico. Quanto à química elementar, o teor de hidrogênio foi o único que não apresentou diferença significativa entre as biomassas e o bagaço de cana apresentou os melhores valores de oxigênio e enxofre, além de alto teor de carbono. Em relação à densidade energética e ao IVC, o cavaco de eucalipto (6,16 GJ/m³ e 307, respectivamente) e a serragem (5,91 GJ/m³ e 32,86, respectivamente), apresentaram os maiores valores. Todas as biomassas avaliadas possuem potencial energético, porém, com base nas variáveis, o bagaço de cana-de-açúcar, a serragem e o cavaco de eucalipto tendem a apresentar maior combustibilidade.

Palavras-chave: Resíduos; Fonte renovável; Bioenergia; Matéria orgânica; Fontes energéticas

1 INTRODUCTION

The use of biomass for energy purposes has grown increasingly over the years. This growth is due to several factors, such as the search for sustainable energy alternatives, less polluting sources for the environment, profit and cost reduction with energy inputs. Furthermore, the use of waste, in addition to economic activities, agriculture, mining, plant extractivism, commerce, industries, among others that cause an increase in the availability and disposal of biomass waste, also influence the growth of biomass use.

Biomass can be defined, according to the National Electric Energy Agency (ANEEL, 2020), as any renewable resource of organic matter, whether of animal or vegetable origin that can be used in energy production. Among the existing biomasses, encompassing those of agricultural origin, such as agro-energy crops (e.g., sugar cane bagasse) and forestry products, by-products, and residues (e.g., wood and charcoal), they serve as input for energy production (SANTOS; NASCIMENTO; ALVES, 2017).

Agricultural and forestry biomass appears as a promising raw material in Brazil for energy generation, as it is a renewable source, with high availability and less polluting when compared to fossil fuels that contribute to the emission of greenhouse gases. Furthermore, biomass can be a complementary energy source, in addition to providing the use of waste that is often discarded in inappropriate places or open-air burning.

It is known that the inadequate disposal of waste in open areas, such as dumps or landfills, can cause a series of environmental problems, besides health problems, such as neglected diseases. This fact persists in Brazil due to the high generation and non-reuse of residues, reflecting an unsustainable model of waste management with potential for reuse. However, the use of biomass as an energy source appears as a solution to this problem (FERREIRA *et al*., 2018; FERREIRA; FERREIRA JÚNIOR; LYRA, 2019).

The Northeast region is privileged in the generation of renewable energy, in addition to the great potential for biomass use, both in crops (eucalyptus, sugar cane, soybeans) and in native areas (Caatinga and Cerrado). Biomass sugarcane is used in various food, beverage, alcohol, and industrial sectors, in addition to providing subsidies for producers in rural areas. Sugarcane bagasse holds significant importance in the Northeast, serving as a source for fuel production. It can be utilized for juice in alcohol production and as raw material for direct burning, using bagasse and straw. (MMA, 2018).

Still regarding its use, biomass stands out in combustion processes in boilers, gasifiers and biodigesters, highlighting that biomass can be used not only to generate electrical energy, but also heat through direct burning and production of biofuels. (SILVA *et al*., 2019).

This article expects to identify and classify materials according to their energy potential through the analyzed variables, seeking to value the reuse of waste. In this way, the intention is to reduce impacts on native forests in the quest for firewood, supporting the conservation of forest resources. Additionally, it contributes to utilizing waste with potential applications, which might otherwise be improperly discarded or sent to landfills.

The study aimed to assess the energy potential of various biomasses derived from agricultural and forestry sources, with the goal of utilizing them as a source for energy generation. This was achieved through the characterization of the physical, energetic, and chemical properties of biomasses, including bulk density, moisture content, calorific value, energy density, fuel value index, as well as immediate chemical, molecular, and elemental analysis.

2 MATERIALS AND METHODS

2.1 Materials

The study was carried out with biomass from the production process of the agricultural and forestry sectors in the state of Pernambuco. It aims to verify their energy potential, seeking their use for energy production as an alternative. The biomasses used were:

1– Sugarcane bagasse residue: biomass collected at a sugarcane factory in the metropolitan region of Recife. Sugarcane is used in the sugar and alcohol sector, with the bagasse obtained after the grinding process to extract the juice, generating bagasse with a lower degree of humidity at the end of the process;

2– Shell of *Eucalyptus spp*. clones: biomass of *Eucalyptus spp*. clones. coming from trees from forestry plantations in the Plaster Complex of Araripe-PE, 7 and 8 years of age;

3– Chip of *Eucalyptus spp*. clones: biomass of *Eucalyptus spp*. clones. coming from trees from forestry plantations in the Plaster Pole of Araripe-PE, 7 to 8 years of age;

4– Sawdust residue: biomass collected in a logging company located in the metropolitan region of Recife-PE, obtained through mechanical processing of wood from the species *Pinus sp*., *Hymenaea courbaril* (Jatobá) and *Manilkara bidentata* (Maçaranduba), widely used in the timber industry sector with in the region, and;

5– Urban pruning waste (branches, stems, and leaves): biomass obtained from the pruning of urban trees in Recife. This initiative is carried out in collaboration with the Urban Cleaning Company of the City of Recife (EMLURB/PCR).

For each biomass, composite sampling was carried out, mixed homogeneously to obtain representative samples for determining the studied variables. After collection, they were taken to the Wood Technology and Anatomy Laboratory at the Federal Rural University of Pernambuco (UFRPE) – Recife Campus, where they were stored until their physical, chemical and energetic properties were evaluated.

2.2 Biomass characterization and statistical analysis

The physical properties of the waste, moisture content and bulk density were determined after drying the material in open-air, until reaching equilibrium moisture. The moisture content of the biomass was determined using the gravimetric method using ABNT NBR 14929 (2017), based on the determination of the wet weight. Then, the samples were dried in an oven at 103ºC ±2ºC, until they reached a constant weight. The moisture content was determined by evaluating the wet basis and by the difference between the weights of the sample, before and immediately after being subjected to drying.

Bulk density was determined using ABNT NBR 6922 (1981). To do this, the samples were weighed in a container with known dimensions. The density was determined through the relationship between mass and volume under air-dried conditions.

To determine the chemical and energetic composition, part of the materials were conditioned and dried in an oven at 105ºC ± 3ºC for 24 hours. They were then crushed in a Willey mill to reduce material particles, and sieved using sieves of specific sizes according to their respective analyses from 40 to 200 mesh. The immediate chemical composition analysis was obtained from ground and sieved samples as recommended by the American Society for Testing and Materials (ASTM) D-1762/84 (2013) standard. It determines the contents of volatile material, ash and fixed carbon.

To estabilish the molecular chemical composition (total extractives, insoluble lignin and holocellulose), previously crushed material was used, which passed through a 40 mesh sieve and was retained in the 60 mesh sieve. The procedures were carried out according to Klock *et al*. (2013), Bezerra Neto and Barreto (2011), TAPPI (T264 cm-97) adapted (ethanol/hexane) and TAPPI (T 222 om-02). The holocellulose content was obtained from the difference of the other molecular chemical components.

The elemental composition of the biomasses was determined by an automatic elemental analyzer model Vario Micro Cube. During the analysis, it uses helium as a carrier gas and oxygen for ignition, to obtain the carbon (TC%), hydrogen (TH%), nitrogen (TN%) and sulfur (TS%) content. (NEVES *et al*., 2011; PAULA *et al*., 2011; PROTÁSIO *et al*., 2011a; REIS *et al*., 2012; LOPES, 2017). The oxygen content (TO%) was obtained from the difference of the components.

The superior calorific value (PCS) was determined by an adiabatic calorimetric bomb under specific conditions, based on the methodology of ASTM E-711 (1987) and ISO 1928 (2009). This method is employed to obtain the gross calorific value, with the water present in the biomass remaining in a liquid state. The calculation is derived from the observation of temperature changes before and after combustion. The Lower and Useful Calorific Power was obtained according to Parikh, Channiwala and Ghosal (2005).

Energy density, which is the amount of energy contained per unit volume of a fuel, was obtained by the product of bulk density and higher calorific value (OLIVEIRA *et al*., 2017). The fuel value index (FVI) was determined according to Purohit and Nautiyal (1987), adapted, using the bulk density. Therefore, the higher the index, the better the fuel value.

Regarding statistical analysis, the design adopted in the research was completely randomized with five treatments: sugarcane bagasse, eucalyptus bark and chips, sawdust and pruning (leaves, stems, branches), with three replications being carried out for each analysis, considering the type of biomass as a variation factor. The data were subjected to analysis of variance (ANOVA). When differences were assumed, the treatments were compared using Tukey's mean test, at 95% probability. Statistical analyses were carried out using the Rbio software.

3 RESULTS AND DISCUSSIONS

3.1 Physical and chemical characterization of biomasses

According to the results obtained through the analysis of variances (ANOVA), the variables of moisture content, bulk density, immediate chemical analysis and molecular chemistry obtained a significant difference at 95% probability by the Tukey test between the biomasses, showing a difference in the composition of the material.

It was found that sugarcane bagasse presented the highest values for the total extractives content (24.90%), the lignin content (27.31%) and the lowest holocellulose content (32.22%). Eucalyptus chips had the lowest total extractives content (7.58%) and the highest holocellulose content (72.55%), while sawdust had the lowest insoluble lignin content (16.58%).

As for the elementary chemical analysis, it is observed that all variables, except the hydrogen (H) content, present a significant difference between the biomasses. As for carbon content (C), eucalyptus bark was the only biomass that showed a statistical difference regarding the others, where it obtained the lowest value. It was observed that there was no significant difference for the hydrogen (H) content, therefore, the Tukey test was not performed for this variable.

Table 1 Shows the average values for moisture content, bulk density, immediate chemical analysis, molecular chemistry and elementary chemistry of biomass.

Moisture content is the amount of water in biomass, being an important index in the use of biomass as an energy source, as it influences the calorific value of the material, as well as the combustion process. The average moisture content of the biomasses, measured on a wet basis after exposure to open-air drying until reaching equilibrium conditions with the ambient moisture, was below 13%, except for the eucalyptus bark biomass, which recorded 15.46% moisture.

Table 1 – Average values for moisture content, bulk density, immediate chemical analysis, molecular chemistry and elementary chemistry of biomass

Treatments	Sugarcane bagasse	Eucalyptus Bark	Eucalyptus Chip	Sawdust	Pruning
TU (%)	13,23 ab (0,32) (2,46)*	15,46 a (1,86)(12,02)	11,97 b (0,04) (0,37)	11,64 b (0,10) (0,88)	12,12 b (0,65) (5,35)
DG (Kg/m^3)	143 c (9,49) (6,62)	192 b (4,38) (2,28)	342 a (1,16) (0,34)	326 a (20,74)(6,36)	148 c (28,10) (19,01)
TMV (%)	72,03 d (0,72) (1,00)	74,09 c (0,31) (0,42)	82,75 a (0,84) (1,01)	76,23 b (0,31) (0,40)	69,70 e (0,84) (1,20)
TCZ (%)	15,56 a (0,44) (2,83)	5,28 c (0,20) (3,77)	0,40 e (0,00) (0,17)	3,69 d (0,52) (14,18)	12,06 b (0,61) (5,11)
TCF (%)	12,41 d (1,09) (8,79)	20,63 a (0,48) (2,34)	16,85 c (0,84) (4,97)	20,09 ab (0,23) (1,17)	18,24 bc (0,88) (4,83)
TET (%)	24,90 a (1,92) (7,72)	13,97 b (0,68) (4,89)	7,58 c (2,02) (26,71)	11,28 bc (0,86) (7,65)	13,89 b (1,59) (11,43)
TL (%)	27,31 a (2,12) (7,76)	19,99 b (2,42) (12,10)	19,48 b (2,45) (12,57)	16,58 b (2,34) (14,12)	19,82 b (2,48) (12,49)
THC (%)	32,22 c (2,82) (8,76)	60,76 b (3,25) (5,35)	72,55 a (2,91) (4,01)	68,41 a (1,68) (2,45)	54,22 b (2,97) (5,47)
C (%)	43,47 a (0,25) (0,58)	40,47 b (0,61) (1,51)	43,33 a (0,35) (0,81)	44,23 a (0,11) (0,26)	43,87 a (0,58) (1,33)
H (%)	5,00 (0,17) (3,46)	5,03 (0,06) (1,15)	5,13 (0,15) (2,97)	5,00 (0,10) (2,00)	5,03 (0,15) (3,03)
O (%)	31,76 d	44,92 b	47,82 a	43,54 b	36,67 c
N (%)	3,93 a (0,25) (6,40)	3,90 a (0,20) (5,13)	3,00 b (0,17) (5,77)	3,13 b (0,11) (3,68)	2,07 c (0,15) (7,39)
S (%)	0,28 b (0,03) (9,45)	0,40 a (0,02) (5,00)	0,31 b (0,00) (1,84)	0,41 a (0,00) (1,42)	0,31 b (0,01) (4,98)

Source: Author (2024)

In where: DG = Bulk density; TU = Moisture content; TMV = Content of volatile materials; TCZ = Ash content; TCF = Fixed carbon content; TET = Total extractives content; TL = Lignin content (Klason); THC = Holocellulose content; C = Carbon; H = Hydrogen; O = Oxygen; N = Nitrogen; S = Sulphur. *Values in parentheses correspond to the standard deviation and coefficient of variation (%), respectively. Means followed by the same letters in each line do not differ from each other using the Tukey test at 95% probability.

According to Parigot (2014), some experts indicate that biomass has a moisture content on a wet basis below 30%. This is already followed by several companies that sell biomass and agree with the literature. Foelkel (2016) reported that moisture contents between 10% and 13% are desirable, as they interfere with the energy of the fuel. Therefore, at least air drying of biomass for energy use is recommended.

Outdoor drying tends to reduce humidity, since high humidity levels reduce the amount of energy in the fuel, having a negative influence on the calorific value. Furthermore, it can also increase transportation and equipment maintenance costs, requiring a greater amount of biomass to generate the same amount of energy during combustion compared to another fuel with a lower moisture content.

For bulk density, it was found that eucalyptus chips and sawdust were those that obtained the highest values, 342 kg/m³ and 326 kg/m³, respectively. For biomasses with low density values in bulk or source far from the consumer, the solution is homogenization, densification, pelletization and briquetting of the fuel to increase the energy density of waste and consequently its calorific value, in addition to reducing transport costs (VALE *et al*. 2011; JACINTO, 2017).

These values are similar to those found in the study by Corradi (2021), where the bulk density for eucalyptus chips was 361 kg/m³ at the age of 10 years. In the case of wood used for energy purposes, the greater its density and lignin, the greater its combustibility (MACHADO; VOGUEL; SILVA, 2014). Unlike lignin, the density of wood increases over time, that is, the younger the wood, the lower its density, thus affecting its calorific value, which is unfeasible for use as an energy input (KLOCK *et al*., 2005; LIMA, 2010; NEVES, 2012). Therefore, the highest density value in the study by Corradi (2021) can be explained by this fact, as the age of the eucalyptus chips is 10 years, while those in this study are 7 and 8 years.

Immediate analysis is extremely important in the characterization of biomass, as it helps to understand the biomass burning process. For energy production, the material is expected to have a low ash content and high fixed carbon value, as these are linked to calorific value.

Regarding the content of volatile materials, eucalyptus chip and sawdust biomass presented the highest values, with 82.75% and 76.23%, respectively. Therefore, they generally tend to have faster ignition in the initial stages of combustion at lower temperatures, facilitating the burning of biomass. However, the burning process in general may be affected, as there are difficulties in controlling volatiles. Pruning waste, on the other hand, has a low value and tends to have the opposite behavior, that is, a slower ignition. The chip presented one of the lowest fixed carbon content values, which can be justified by the inverse proportion mentioned by Protásio *et al*. (2011b) and Jacinto (2017).

It is preferable for biomass to have a low ash content. Eucalyptus chips presented the lowest value, 0.40%, in line with what was mentioned by Chaves *et al*. (2013), in which eucalyptus species have the common characteristic of low wood ash contents, generally not exceeding 1%.

These data are opposite to those obtained for sugarcane bagasse and pruning biomass, which presented high values (15.56% and 12.06%, respectively), indicating that the quality of the biomass may be compromised depending on the composition of other elements. This fact can be explained, as Yaman (2004) reported, by stating that the ash content in herbaceous and agricultural species is around 15%.

The amount of ash will influence the formation of compounds during thermal decomposition, which could impact the material's burning equipment, as they are mineral components. The high values found for the studied biomasses may also be a function of the harvesting, transport, and storage process, given possible contamination with the soil. Furthermore, there may be impurities in the material arising during these processes (COSTA *et al*., 2020). When biomass is used in furnaces, the ash can melt and produce slag deposits and scale (GARCÍA *et al*., 2013).

As for fixed carbon content, biomasses that presented the highest values were eucalyptus bark, with 20.63%, and sawdust, with 20.09%. Thus, sawdust, besides having rapid ignition at low temperatures, will also have a longer combustion time. This implies, as per Juizo, Lima and Silva (2017), better yield and quality for carbonization and burning. Moreover, according to Costa *et al*. (2017), it demands less biomass to burn, leading to fewer interventions in the supply process. On the other hand, eucalyptus chips, which have a faster ignition due to the high value of volatile materials, will not have a longer combustion time than sawdust and eucalyptus bark, as their fixed carbon value is lower but close to the highest results obtained.

To present an ideal burning pattern for energy production, biomass must have an average fixed carbon content of around 17.40% (OLIVEIRA *et al*., 2017). According to Brito and Barrichelo (1978), for several kinds of eucalyptus, fixed carbon varies between 10% and 25%. Values within this range were obtained by Juizo, Lima and Silva (2017), with levels ranging between 14.47 % and 18.89% for wood from nine eucalyptus species.

Regarding the total extractives content, sugarcane bagasse obtained the highest value, 24.90%, followed by pruning, 13.89%. Eucalyptus bark obtained 13.97%, sawdust 11.28%, and eucalyptus chips 7.58 %, with the latter exhibiting the lowest value among the biomasses. According to Klock *et al*. (2005), dry wood is composed of 3% to 10% extractives, which contribute to the calorific value. Therefore, the amount of extractives present in wood is a positive factor for direct combustion, as it facilitates the decomposition of the wood structure (PROTÁSIO *et al*., 2013b).

As for lignin content, the results obtained in this research varied from 16.58% to 27.31%. The biomass that presented the highest value was sugarcane bagasse, with 27.31%. Sawdust presented 16.58%, being the lowest value, and the other biomasses in this study presented around 19%.

These variables are important in the thermal degradation process, influencing the generation of energy by biomass. Lignin is the component of biomass that presents the greatest resistance in thermal degradation processes (PUÑAL *et al*., 2012; WANG, 2011), being of great importance in the energy use of biomass. Furthermore, low levels of extractives can contribute to increasing the calorific value.

Extractives and lignin have a lower amount of oxygen in their composition when compared to hemicelluloses and cellulose, according to Silva *et al*., (2014). Furthermore, these wood components have complex structures with more carbon, which tends to release a greater amount of energy during the combustion process. Another significant factor that affects the extractive content is age. Soares *et al*. (2015) reinforce that the younger the tree species, the higher the extractive content. In this study, *Eucalyptus spp.* species with different ages were studied.

For the values obtained in this study for the holocellulose content variable, eucalyptus chips presented the highest value (72.55%), while the lowest value was found in sugar cane bagasse, with a content of 32.22%. Therefore, the lower the holocellulose content and the higher the extractive and lignin content, the better it is for the thermal use of biomass (BUFALINO *et al*., 2012; PROTÁSIO *et al*., 2012).

According to Carvalho *et al*. (2021) the heterogeneity of materials and impurities found in the bark (silica), pruning (different species and different parts, leaves), and sawdust can interfere with lignin and extractive analyses. Holocellulose does not have a positive influence on the use of biomass for energy purposes, as a high content tends to reduce the calorific value and density of the biomass. In other words, the material would be consumed faster, resulting in less efficient utilization of the energy from the residue. In the study by Neves (2012), age was a determining factor in wood holocellulose levels, as the older the age, the lower the holocellulose content.

Regarding the results obtained in the elementary chemical analysis, eucalyptus bark was the only one that differed significantly from the other biomasses, with this content of 40.47% being the lowest value found for the elemental carbon content. Among biomasses, the highest value was sawdust (44.23%), while pruning, sugarcane bagasse and eucalyptus chips obtained 43.87%, 43.47% and 43.33 %, respectively.

Biomasses have (C, H, O, N and S) in their elemental composition. However, sulfur is in a smaller proportion than the other elements. Therefore, the analysis plays an essential role in the use of wood as biofuel. To evaluate a biomass, several analyses are relevant. Nevertheless, the evaluation of the elemental composition is also relevant due to the carbon and hydrogen contents when inversely proportional to the amount of oxygen, correlating with the increase or decrease in calorific value. Plant biomass that has a high carbon and hydrogen content and low oxygen content is expected to have a higher calorific value. (VALE *et al*., 2000; YAMAN, 2004; PAULA *et al*., 2011, PROTÁSIO *et al*., 2011a).

There was no significant difference in hydrogen content, which remained at 5% for all biomasses studied. Regarding the oxygen content, lower values are preferable as they negatively correlate with the calorific value. Sugarcane bagasse (31.76%) was the lowest content found, while eucalyptus chip biomass exhibited the highest oxygen content at 47.82%.

Therefore, low values are desirable, as oxygen correlates negatively with calorific value. Oxygen, when in greater quantity, tends to reduce the calorific value of biomass, despite being essential for the combustion of the material. Thus, biomasses with higher carbon and hydrogen contents, along with lower oxygen and ash contents, are desirable. This combination will contribute to better performance in bioenergy production (PROTÁSIO *et al*., 2011a; LOPES, 2017).

For nitrogen, the highest value was recorded in sugarcane bagasse (3.93%), while the lowest was found in pruning residue (2.07%). Eucalyptus bark obtained 3.90%, sawdust 3.13%, and eucalyptus chips 3.00%. The low nitrogen content does not compromise the use of biomass for bioenergy; however, lower levels of this component are preferable in the biomass. This is due to its negative correlation with calorific value and high toxicity, thus contributing to environmental pollution (HUANG *et al*., 2009; REIS *et al*., 2012).

Regarding sulfur content, the biomass with the highest value was sawdust (0.41%) and the lowest was sugarcane bagasse (0.28%). The biomass of eucalyptus chips obtained the value of 0.40%, while eucalyptus chips and pruning residue both had 0.31%. The sulfur content does not have a positive correlation with the calorific value; therefore, low values of this variable are desirable. For steelmaking, the value must be below 0.5%, thus, the values are acceptable for this purpose (NEVES, 2012; REIS *et al*., 2012).

In this sense, several factors can interfere and influence the quality of biomass for energy purposes, such as physical, chemical, and energetic variations, as well as geographic location, genetics of the species, climate, spacing, among other factors. For this reason, this article reinforces the importance of studying and understanding the properties of the utilized species. This knowledge aids in precisely determining the intended purpose, maximizing utilization, and enhancing the energy quality of the biomass.

3.2 Energy composition of biomass

Table 2 shows the results of PCS, PCI, PCU and energy density.

Table 2 – Average values of the energetic properties of the evaluated biomasses

Treatments	Sugarcane bagasse	Eucalyptus Bark	Eucalyptus Chip	Sawdust	Pruning
PCS (KJ/Kg)	18405 a (229,38)(1,25)	17494 c (254,61)(1,45)	18024 ab (93,98)(0,52)	18115 ab (105,57)(0,58)	17785 bc (229,52)(1,29)
PCI (KJ/Kg)	18135 a (229,38)(1,26)	17222 c (254,61)(1,48)	17747 ab (93,98) (0,53)	17845 ab (105,57)(0,59)	17514 bc (229,52)(1,31)
PCU (KJ/Kg)	15656 a (220,22)(1,41)	14470 b (532,35)(3,68)	15551 a (86,59) (0,56)	15699 a (108,39)(0,69)	15317 a (94,07) (0,61)
DE (GJ/m³)	1,62 c (0,17) (6,63)	3,36 b (0,03) (0,83)	6,16 a (0,05) (0,82)	5,91 a (0,35) (6,01)	2,63 b (0,51) (19,25)

Source: Author (2024)

In where: PCS = Higher calorific value; PCI = Lower calorific value; PCU = Useful calorific value; DE = Energy density. *Values in parentheses correspond to the standard deviation and coefficient of variation (%), respectively. Means followed by the same letters in each line do not differ from each other using the Tukey test at 95% probability.

For PCS, sugarcane bagasse (18,405 KJ/Kg), sawdust (18,115 KJ/Kg), and eucalyptus chips (18,024 KJ/Kg) were the biomasses that presented the highest values and are statistically similar to each other.

Regarding the upper, lower, and useful calorific value, high values are preferable in a biomass for energy purposes. The calorific value represents the combustion potential, being directly linked to the efficiency of its burning potential, that is, the amount of energy that is released during the thermal degradation of a fuel. To evaluate the capacity and energetic viability of a fuel for energy generation, with the goal of replacing the use of fossil fuels, the calorific value is emphasized as one of the main parameters (SANTOS *et al*., 2011).

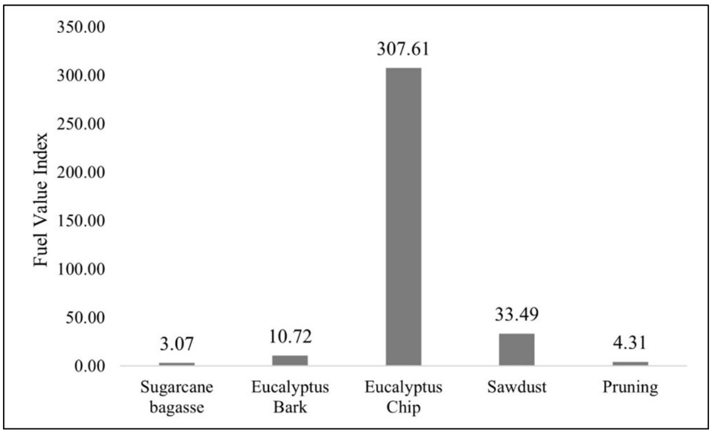
For energy use, a high calorific value in biomass is desirable, as it represents the combustion potential, being directly linked to the efficiency of its burning capability. In other words, the amount of energy that is released during the thermal degradation of the fuel. However, the fuel depends on several factors such as density, humidity, chemical composition, energy, and the type of biomass.

Statistically, the lower calorific value showed the same behavior as the higher calorific value, with sugarcane bagasse (18,135 KJ/Kg) being the highest value, followed by sawdust (17,845 KJ/Kg), and eucalyptus chips (17,747 KJ/Kg). As for the useful calorific value, sugarcane bagasse and sawdust presented 15,656 KJ/Kg and 15,699 KJ/Kg, respectively. Eucalyptus bark, on the other hand, had the lowest value, with 14,470 KJ/Kg.

Energy density, which is the energy contained per unit volume of a material, is one of the main parameters for evaluating the energy potential of a biomass, affecting its quality, and being linked to its composition. Regarding the values obtained for energy density in the evaluated biomasses, the one with the highest value was eucalyptus chips (6.16 GJ/m³), followed by sawdust (5.91 GJ/m³). Sugarcane bagasse residue presented the lowest value among the others (1.62 GJ/m³), together with pruning (2.63 GJ/m³).

Figure 1 shows the values obtained for the FVI, where the average value of the ideal characteristics of a biomass, according to the index, is considered in the calculation, such as high calorific value, high bulk density, low ash content, and low moisture content. According to the graph, eucalyptus chips presented the highest value, and sawdust the second highest, while the lowest value was obtained by sugarcane bagasse.

Figure 1 – Biomass fuel value index

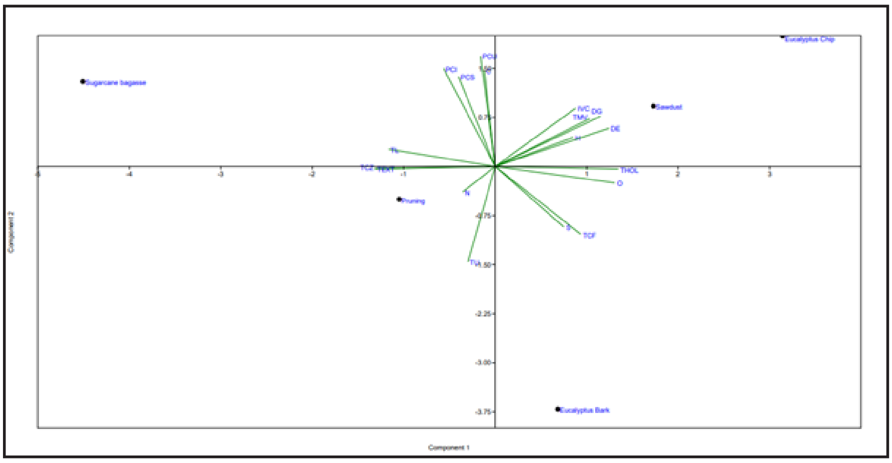


Source: Authors (2024)

3.3 Principal Component Analysis (PCA)

Regarding the main component analysis (PCA), using the biplot graph (Figure 2), it is possible to observe the outcomes of the analysis concerning the variables analyzed for the biomasses. This allows to group samples with similar profiles, as well as understand the relationship between them. The first two components explained 76.75% of the total data variability, with 48.15% and 28.60% for components 1 and 2, respectively. The most significant information is with in these two main components.

Figure 2 – Treatment ordering diagram considering the scores and eigenvectors of main components 1 and 2



Source: Authors (2024)

When analyzing the contribution of each variable to the main components, it appears that the variables with the greatest contribution to component 1 refer to the chemical composition of biomass (all immediate, molecular and elemental chemistry with the exception of Carbon). And for component 2, the variables relating to calorific value (higher, lower and useful), carbon content, moisture content, FVI and energy density were those that presented the greatest contributions. Thus, it is possible to distinguish the biomass groups through the desired variables aiming the energy potential. There is a group for the biomasses sawdust and eucalyptus chips, and other separate groups for sugarcane bagasse, eucalyptus bark and pruning.

Given the growth and evolution of society, energy has become an essential resource in various technological, economic and environmental sectors. Consequently, dependence and energy consumption increased, which also contributed to the growth in energy demand. In this way, there is a growing pursuit of alternatives in the reliance on non-renewable resources as energy sources in the global matrix, minimizing environmental impacts.

4 CONCLUSIONS

The biomass with the best energy quality is sugarcane bagasse, as it has the highest upper and lower calorific values, along with a high effective calorific value. The biomass with the lowest energy potential is eucalyptus bark, as it presented the lowest PCS, PCI, and PCU. Biomass from eucalyptus sawdust and chips also has high energy potential, as they presented similar PCS and PCI values to sugarcane bagasse, and sawdust presented better PCU. Chips showed better energy density and FVI, followed by sawdust.

The essential variables for the greater calorific value of sugarcane bagasse were molecular chemical analysis, oxygen, sulfur, and carbon contents. Among the biomasses, sugarcane bagasse and pruning had a high ash content, above what is acceptable. However, their use for energy purposes is not unfeasible, and it is necessary to evaluate the purpose.

All the biomasses studied can be used to generate energy, some directly in the cogeneration process, others in boilers and in the production of by-products, such as briquettes. This increases the quality of solid fuel and energy potential, and it is an alternative for better use of residual biomass.

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