Study of combustion of bagasse/straw sugarcane and its atmospheric emissions using a pilot-burner

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Abstract

Purpose: This work conducted experimental combustion on a closed chamber using two different materials: mixture (1:1) sugarcane bagasse/straw and pre-treated biomass. **Methods:** The sampling method was an Andersen cascade impactor with eight stages. The tests were carried out for untreated biomass in four air velocities observed in the sampling duct (4.18; 5.20, 6.85 e 8.21 $m.s^{-1}$). Pre-treated biomass tests were performed at 4.19 $m.s^{-1}$ because, in this condition, the speed was more stable inside the duct. **Results:** During the combustion tests, the concentration of emitted particles was higher for the lower speed range, with an order of $4.19 > 5.40 > 6.85 > 8.21$ $m.s^{-1}$. The higher speeds observed inside the duct behaved as a dragging agent for particulate material. For the tests at the speed of 8.21 $m.s^{-1}$ where the flow inside the duct was 0.088 m^3s^{-1}, this behavior is more evident. Considering the particles corresponding to the fine diameter (< 2.5 μm), these were emitted in a higher concentration, which is due to the biomass combustion process, which results in higher emission of ultrafine particles. The emission factors obtained for PM_{10} for untreated biomass were in the range of 0.414 and 0.840. On the other hand, considering the pre-treated biomass, these factors were 0.70 and 1.51. The EFs of PM from the burning of the pre-treated biomass was higher when compared to untreated biomass, which is mainly due to the higher temperature of the process due to the higher HHV of this material, caused by the removal of hemicellulose and a proportional increase in lignin. **Conclusions:** Furthermore, the emission factors obtained in this study might be useful as input data for air quality modeling in the context of sugarcane's burning biomass, thus contributing to the generation of inventories that include emissions of this nature.

Keywords: combustion, sugarcane, biomass, particle material.

1 Introduction

Currently, the use of fossil fuels represents the major portion of the energy source used in the world, in addition to being used as precursors to various chemicals in the industry [1]. Such behavior refers to the concern about this dependence that is associated with environmental impacts due to the emission of particulate and gaseous pollutants that contribute to the greenhouse effect [2, 3, 4]. One way to mitigate such effects is to use alternative sources of energy and chemicals [5, 6]. The use of lignocellulosic biomass in several processes has been improved to reduce this global dependence, since they can be used directly for the production of heat or depolymerized for the use of its sugars in chemical conversion processes or even in fermentation processes [7].

Brazil is currently the largest producer and processor of sugarcane in the world. For the 2019/20 harvest, around 615 million tons of sugarcane were produced, which were destined for the production of ethanol and sugar [8]. The bagasse remaining from the milling process and the straw from the harvesting process should not be treated only as waste, but as the main energy biomass available in several countries. It is considered that for each ton of processed cane, 280 kg of straw and 280 kg of bagasse are generated [9]. Currently, not is possible to take advantage of all this lignocellulosic biomass that is generated, where the main destinations are still co-generation of electricity and heat within the industrial plant, as a way of making full use of the raw material and reducing the use of fossil diesel fuel. Through cogeneration, a destination for the biomass resulting from the harvest and the milling processes is allowed, in addition to enabling the energy self-sufficiency of these processing units [10].

Thermochemical processes are widely used in the production of electricity, with emphasis on direct combustion technology in which biomass degradation occurs, transforming chemical energy into heat. It is usually used in distilleries because it requires less investment and process control [11]. Factors such as moisture content, calorific value, fixed carbon content, volatile matter, and ash, in addition to the relationship between cellulose and lignin must be considered for the use of biomass as an energy source. However, associated with this practice, air pollutants are emitted, which are combustion products that leave the process on-site [12].

In addition to the particulate material being of great concern due to the harmful effects to health, it is responsible for some atmospheric processes, such as, for example, the dispersion of light. Therefore, evaluations of the properties of these particles are important, which include: concentration, mass, size, chemical composition and optical and aerodynamic properties [13, 14]. Of these, size is the most important, as it makes it possible to relate the source of the particle to its effects on health, visibility and climate; in addition to the determination of secondary properties such as volume, mass, deposition speed and range of particles in the respiratory tract, which are related to the size of the particles [15-17].

Despite the advantages of using biomass to co-generate energy through combustion, the emission of pollutants resulting from this practice, such as, for example, gases and particles are of concern since they cause great environmental impacts, in addition to being harmful to human health [16-19]. Among air pollutants, particulate matter (PM) has been the subject of studies and investigations to better elucidate its formation and emission mechanism; in addition to parameters such as the composition of fuel biomass, humidity, granulometry, the mechanism of operation of the combustion chamber, among other parameters, which influence the efficiency of combustion processes and consequently will impact the number of emissions generated. Thus, it is of great importance to study the impacts of the expansion of ethanol production in Brazil, resulting in more accurate inventories for the burning of these residues, since sugarcane biomass is the main energy crop available in the country [2, 20, 21].

Few studies on emissions of particulate pollutants have been conducted in the context of a closed chamber, which allows extrapolating to what happens in industries, where it is a significant source of emission of particulate pollutants.

Different experimental studies have been carried out to measure emission factors (EF) derived from burning agricultural waste, either in a context the open combustion chambers to simulate open-field burning [22- 24,10], or in a closed combustion chambers with controlled airflow conditions [25-27], to support the emission control strategies and elaboration of PM inventories. The last type of study being insufficient, especially when considering the sugarcane by-products that are widely used for heat and energy production. Therefore, the main objective of this study was the determination of EFs for particulate matter (PM10, PM2.5), because they are specifically relevant to health effects. The experimental study was carried out on a closed combustion chamber using two different raw materials; mixture (1:1) sugarcane bagasse and straw and pre-treatment biomass. The sampling method was with Andersen cascade impactor with 8 stages based on continuous measurements performed under controlled conditions in the flame phase. The advantage of using a closed combustion chamber is the ability to guarantee controlled burning conditions and discard external variables such as characteristic nature of the soil and the climate conditions, which constitute a barrier to on-field burning test reproducibility. In addition, the main chemical species associated with these particles were investigated, since this understanding is important for the determination of tracer species for biomass burning. Furthermore, the emission factors obtained in this study might be useful as an input data for air quality modelling in context the burning biomass of sugarcane thus contributing for the generation of inventories that include emissions of this nature.

2 Material and Methods

2.1 Materials

Sugarcane bagasse and straw (SB) used in this study were obtained at the ethanol-sugar mill Santa Cruz-São Martinho, located in Americo Brasiliense, São Paulo, Brazil. The sugarcane biomass was sun-dried until moisture of 10% approximately and milled in a Forage Crushers TRF-400 (particle size 5 mm). Sulfuric acid (95-97%) were purchased from Merck Millipore, Brazil. All chemicals were analytical grade or above and were provided by Merck Millipore, Brazil.

2.2 Pre-treatment of sugarcane biomass

The sugarcane biomass (1:1 of straw:bagasse) diluted-acid pre-treatment was performed in a 350-L stainless steel reactor (located at Brazilian Bioethanol Science and Technology Laboratory-CTBE, Campinas, Brazil) under the following conditions: 0.5 % (w/v) H_2SO_4, solid/liquid ratio of 1:10, 140 ºC for 15 min.

After process hydrolysis, the mixture was filtrated to separate the hemicellulosic hydrolysate and the solid fraction. The solid fraction was washed with water to remove residual acid, sun-dried until moisture content around 10% and stored at room temperature for further characterization and combustion tests.

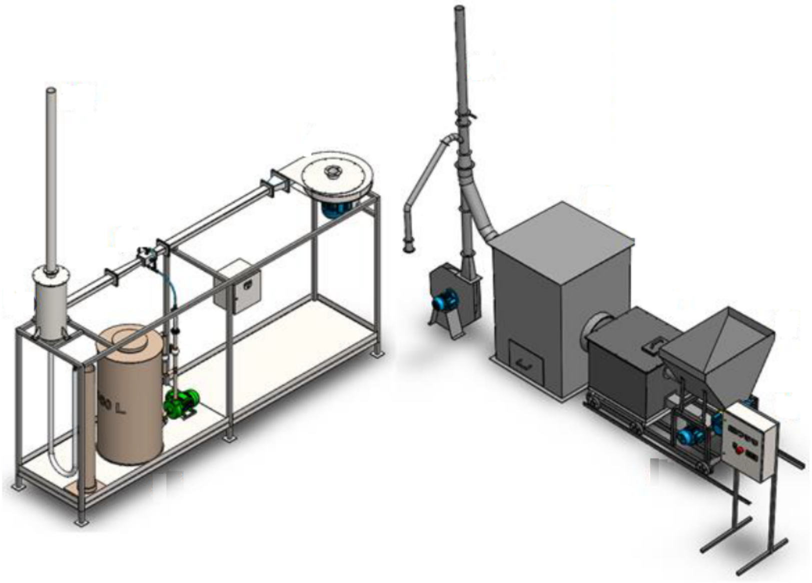
The sugarcane biomass after and before pre-treatment were characterized using the standard methodology for characterization of biomass structural carbohydrates and lignin from the National Renewable Energy Laboratory - NREL [29]. The immediate properties of biomass: moisture content, volatile matter, ash, and fixed carbon were determined using the European standards (CEN/TS 15148, CEN/TS 14775 and CEN/TS 14774-3).

2.3 Combustion tests

2.3.1 Pilot-scale combustion chamber

The combustion tests were carried out in the experimental module manufactured by the company SELLER (Fig 1), it is 13 m long and 4 m wide with automated functions. The unit consists of a rotary feeder, combustion chamber, flame compartment, cyclone, blowers, and exhaust ducts. It has an installed power of 8.1 kW. The tests were carried out in four air velocities observed in the sampling duct (4.18; 5.20, 6.85 e 8.21 m s^{-1}). The tests were performed in duplicate and were used approximately 6 kg of biomass. Feeding is carried out upper, where an endless screw that transports the biomass, which is connected to the combustion chamber and allows for the fuel inlet.

Fig 1. Pilot-burner for biomass combustion and particles collection test



The primary combustion air was performed from below the grate and secondary air from above the fuel bed. After the combustion chamber, the process gases are directed to the flame compartment unit. The monitoring takes place the temperature of the gases was determined by means of a type K thermocouple. A blower performs the injection of secondary air by boosting and diluting the combustion gases, a part directed to the exhaust chimney and another part of the gases to a set of blowers that allow the directing of the gases to the sampling chimney.

2.3.2 Particle collection

The collection took place with an Andersen cascade impactor with 8 stages with fractionation of particles 10.0 - 0.4 µm in diameter. Previous the sampling, fiberglass filters (AP 15 Merck Millipore diameter 81 mm) were baked for 24 h at 105 °C and cooled in a desiccator. After collecting the particles emitted by the burning of biomass, the filters of each stage were folded in half and stored in a freezer at -14 ºC until they were analyzed. Each filter was weighed under controlled conditions of temperature and humidity in a Mettler Toledo AX26 analytical balance with an accuracy of ± 0.00001 g.

The impactor was positioned in one of the chimneys in the smoke plume and was started after the biomass was fully in the flame phase, observed inside the combustion chamber and the temperature of the combustion gases reached values close to 200 ºC. A constant sampling flow rate of 37.5 L min^{-1} was controlled by using a vacuum pump, a control needle valve, and a flow meter.

The tests with sugarcane biomass pre-treated (test 5) were performed at a speed of 4.19 m s^{-1} because it is the condition in which there is less influence of the speed parameter inside the duct. For the other experiments, the fuel material used was a 1:1 mixture of straw and sugarcane bagasse.

The particle collection tests lasted 5 minutes and the feeding frequency was fixed at the pilot burner control module at 570 rpm (electric motor WEG - model W22) and the conditions used are described in Table 1.

Table 1. Settings used during the combustion tests for the sugarcane biomass.

Test	Average chimney speed (m s^{-1})	Chimney sampling flow (m^3 s^{-1})	Feeder Speed (rpm)	Sampling time (min)
1	4.2 ± 0.2	0.045	570	5
2	5.4 ± 0.2	0.057	570	5

3	6.9 ± 0.4	0.073	570	5
4	8.2 ± 0.5	0.088	570	5
5	4.2 ± 0.2	0.045	570	5

In this step, it was possible to calculate the emission factor (EF) for $MP_{2.5}$, MP_{10} and soluble ions in g kg^{-1} (g of particles emitted per kg of burnt dry biomass), using the following equation (Amaral et al., 2016).

$$FE = \frac{XPM_y \times V_{total}}{mass_{fuel}} \tag{1}$$

Where, XMPy is the PM concentration of the corresponding fraction (mg m^{-3}), V_{total} (m^{-3}) is the total volume of air flowing through the chimney during the sampling period and mass fuel is the dry mass of biomass consumed in the sampling (kg).

2.4 Analysis

2.4.1 Elemental analysis for biomass samples

For the elemental analysis of the biomass samples, an Elemental Analyzer CHNS/O 2400 series II (Perkin Elmer) was used. The elemental analyzer makes it possible to determine carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O). The technique used for the determination of C, H, N, S is combustion in pure oxygen medium. The determination of O is performed by the pyrolysis technique in a helium/hydrogen mixture.

2.4.2 Determination of calorific power

The determination of the calorific value can be estimated from equations and based on the results obtained from the elementary analysis (C, H, N, O, S) and humidity (H). Therefore, with these data, the HHV (higher heating value) was determined, which considers the energy released in the form of heat and the energy spent on vaporization of water, the LHV (lower heating value) which considers only the available energy.
The equations proposed by Mendeleev (1949) were used to determine the LHV and HHV of the biomass:

$$\text{LHV} = 339C + 1030H - 109(O - S) - 24\text{H} \tag{2}$$

$$\text{HHV} = 2.3381 + 0.351C \tag{3}$$

2.4.3 Thermal characterization: TGA/DTG

The thermogravimetric experiments were performed on a simultaneous thermal analyzer SDT-Q600 TAA and the results were analyzed using the TA Advantage 2005TGA software. The temperature range evaluated was 30 - 1200 ºC, with a heating rate of 10 ºC min^{-1}. Approximately 5 mg of each sample was inserted into a 90 µL (5x5 mm) alumina crucible. The inert atmosphere was established with the insertion of nitrogen with a flow rate of 80 mL min^{-1} to prevent oxidation of the sample.

2.4.4 Extraction of soluble ions

The glass fiber filters used in the cascade impactor were cut into pieces of 4 cm^2 of area for each sampler stage in order to extract the soluble ions present in the PM. The species was solubilized in Milli-Q Millipore deionized water (18 MΩ resistivity) and the solution was submitted to mechanical shaking for 40 minutes. The resulting solutions were filtered with membrane (Millipore) Millex-HV 0.45 µm and the filtrate was chromatographic analysis. For the determination of the water-soluble ions in the PM, an Ion Chromatograph (Thermo Scientific), model ICS 5000 analytical was used.

3 Results and discussion

3.1 Characterization of sugarcane biomass

Table 2 shows the results obtained in the characterization of the tested lignocellulosic materials; straw, bagasse and sugarcane biomass pre-treated. The estimation of its constituents, as well as the properties of these biomasses allows a prediction of their behavior during combustion, as it will define the calorific value of the material.

Table 2. Chemical characterization of the investigated biomass

Parameter	Straw	Bagasse	Sugarcane biomass pre-treated (SBP)
Elemental analysis (wt%)			
C	44.5	45.5	48.7
H	5.6	5.5	6.2

N	1.1	0.7	0.7
O	39.2	35.4	40.4
S	1.3	1.2	1.4
H/C	0.2	0.1	0.1
O/C	0.9	0.8	0.8
Proximate analyses (wt%)			
Moisture	8.2 ± 0.3	7.2 ± 0.3	6.8 ± 0.2
Volatile matter	80.0 ± 0.7	88.4 ± 2.2	84.3 ± 0.9
Fixed carbon	13.6 ± 0.9	9.12 ± 2.4	12.4 ± 0.9
Ashes	5.9 ± 0.6	2.3 ± 0.2	3.1 ± 0.02
LHV (MJ/kg)	15.2	16.0	17.2
HHV (MJ/kg)	18.0	18.3	19.4
Chemical composition (wt%)			
Cellulose	37.5 ± 1.8	36.6 ± 0.3	50.4 ± 0.2
Hemicellulose	26.3 ± 1.4	28.4 ± 0.3	5.8 ± 0.04
Lignin	23.9 ± 0.6	22.0 ± 0.6	33.6 ± 0.4
Extractives	16.5 ± 1.1	11.4 ± 1.6	-
Acetyl groups	4.5 ± 0.2	2.9 ± 0.1	0.4 ± 0.01

The elemental composition for straw and bagasse was similar, with a greater difference in oxygen content. These results were in accordance with previous investigations. Cardoso et al., [30] reported values of 47.03 %; 5.5 %; 1.08 % and 46.34 % for carbon, hydrogen, nitrogen, and oxygen; respectively. Carbon and hydrogen are important elements for the release of heat during the combustion process. For energy purposes, biomasses with a low percentage of oxygen and a high carbon content are desirable [31]. The results obtained for C varied between 44.5 and 48.67 % (Table 2), with straw being the fraction with the lowest C content and SBP with the highest content. The observed proportion of H/C and O/C was kept approximately the same for all biomass, the values obtained were similar with others reported for lignocellulosic biomass [30, 26, 31]; the low ratio is desirable to reduce the emission of gases and vapors. High levels of C and H contribute positively to the calorific value during the burning process due to the conversion of CO, CH_4 e H_2 [34], behavior observed for the analyzed biomasses, where the SBP that presented the highest HHV is also the biomass with the highest levels of C and H.

The results of the proximate analysis are also described in Table 2. The moisture content of the biomasses was 8.23; 7.18 and 6.82 % for straw, bagasse and SBP; respectively. For use in thermochemical processes, < 10 % humidity is recommended, values higher than this makes the process energetically unfavorable, as it requires additional heat to evaporate the present water, reducing the efficiency of thermal conversion of the biomass. According to the proximate analysis, the bagasse has a higher volatile matter content when compared to the other two biomasses, thus being a more reactive and easily devolatilized biomass.

The ash contents were 5.90; 2.31 and 3.08 % for straw, bagasse and SBP; respectively. The higher ash content in straw is associated with problems during the thermochemical conversion process, which reduces the burning rate, increasing the incidence of incrustations and corrosion in the reactors [35]. On the other hand, bagasse was the material with the lowest ash content. The fixed carbon value for the biomasses was also determined, the values ranged from 9.12 to 13.55 % m/m db. The straw has a fixed carbon content higher than the other two tested biomasses.

The main lignocellulosic constituents are cellulose, hemicellulose, lignin, extracts, and ash (Table 2), which have different thermal decompositions. The results found for the bagasse are similar to the results obtained by Kanwal *et al.,* [36] which reported 36.9 % cellulose, 26.3 % hemicellulose, 19.2 % lignin and 12.7 % extractive. This was also observed for straw, in a study by Oliveira *et al.,* (2014) who reported cellulose, hemicellulose, lignin, extractive and ash contents of 38.1 %; 29.2 %; 24.2 %; 5.9 % and 2.5 %; respectively. The cellulose and lignin content for SBP were 50.37 % and 33.55 %; respectively. It is noted that these lignocellulosic constituents after the acid hydrolysis increased proportionally due to the solubilization of the constituent sugars of hemicellulose (xylose, glucose, and arabinose). This indicates that the hydrolysis conditions employed were appropriate to extract the sugars contained in the hemicellulosic fraction. The variations observed in the composition of lignocellulosic biomass can be attributed to the characteristics of the material; such as age, storage time, variety, cultivation and harvest conditions [38].

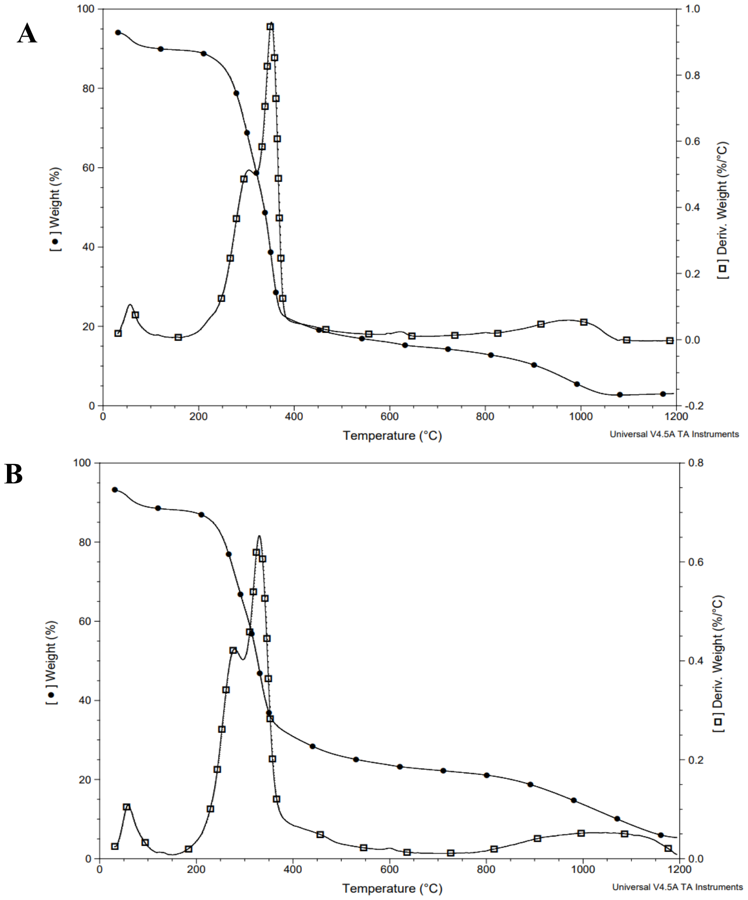
The calorific value represents the amount of energy released from a fuel during its complete combustion, being important its determination to evaluate its use as fuel. The calorific value found for straw and bagasse was similar, in agreement with the results obtained by Ferreira [39] who reported a calorific value for sugarcane straw of 16.42 MJ/kg. The equations proposed by Mendeliev were used to determine the LHV and HHV.

According to the equation, the content of C and H increases the calorific value of the fuel, while the content of O decreases, as it behaves as an oxidizing agent, decreasing the fuel power. The highest calorific value found in the evaluated samples was for the pre-treated biomass of 19.42 MJ/kg, due to the higher C and H content in the material, due to the removal of the hemicellulosic fraction, and the lowest calorific value was for straw, 17.96 MJ/kg.

Thermogravimetric analysis is a good tool to understand the biomass decomposition process. The thermal behavior of biomasses; SBP, straw and sugarcane bagasse are shown in Figure 2 through the TG and DTG curves.

Sugarcane bagasse (SB) TG curves reveal that the first peak of degradation occurred at a temperature of approximately 60 °C, the second and third peaks occurred at 310 °C and 350 °C. There were four main events of mass loss, the first of which is the evaporation of water and removal extractives, in the range of 25 - 150 °C, attributed to the humidity and other compounds of the sample equal to 3.68 ± 0.07 %. The second event in the range of 150 - 320 °C (29.92 ± 0.21 %), the third at 320 - 400 °C (37.71 ± 0.68 %) and the fourth event at 400 - 1200 °C (17.24 ± 1.02 %) attributed to hemicellulose, cellulose, and lignin; respectively. With a residue of 5.00 ± 1.95 %, attributed to the ash content or undegraded part of the sample. Hemicellulose has low thermal stability and decomposition occurs at lower temperatures. The peak followed by the hemicellulose shoulder corresponds to the decomposition of cellulose, which is the main component of the biomass cell wall, finally, the degradation of lignin occurs more slowly and over a wide temperature range [40].

Fig. 2. TGA and DTG profiles for sugarcane bagasse (A), straw (B) and sugarcane biomass pre-treated (C) under atmospheres of nitrogen in temperature range the 30 – 1200 ºC at heating rate of 10 ºC min^{-1}



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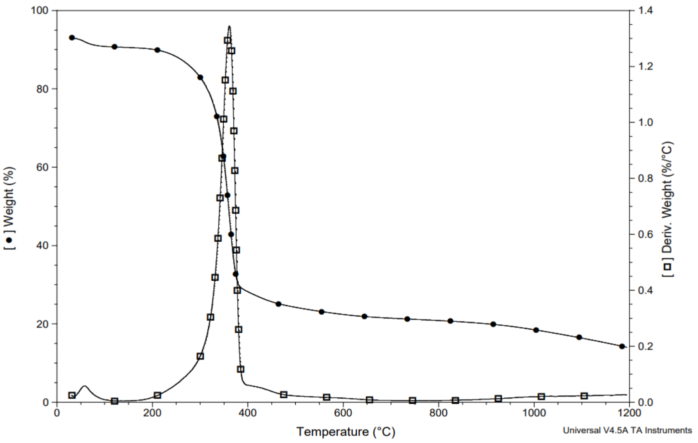


In Figure 2 (b) it is noted that the first peak of the DTG curve for sugarcane straw also occurred at a temperature of approximately 60 °C, the second and third peaks occurred at 280 °C and 335 °C. The second event in the range 150 - 300 °C (29.92 ± 0.21 %), the third at 300 - 400 °C (37.71 ± 0.68 %) and the fourth event at 400 - 1200 °C (17.24 ± 1.02 %) attributed to hemicellulose, cellulose, and lignin; respectively. With a residue of 5.00 ± 1.95 %, attributed to the ash content of the sample or non-degraded part.

For SBP (Fig.2c), the first peak occurred at a temperature of approximately 60 ºC, the second and third peaks occurred in the temperature ranges of 115 ºC and 315 ºC. This TGA curve presented three main degradation events, the first being due to water evaporation, in the range of 25 - 125 °C, attributed to the sample humidity equal to 1.80 ± 0.57 %. The second event in the range of 125 - 400 °C and the third at 400-1200 °C, with a mass loss of 56.02 ± 6.45 %; 12.74 ± 1.42 %; respectively. The second shoulder that usually occurs right after the water evaporates, attributed to hemicellulose did not appear, indicating that the pre-treatment process contributed to the removal of hemicellulose. With a residue of 14.03 ± 0.69 %, the latter can be attributed to the ash content of the sample or undegraded biomass.

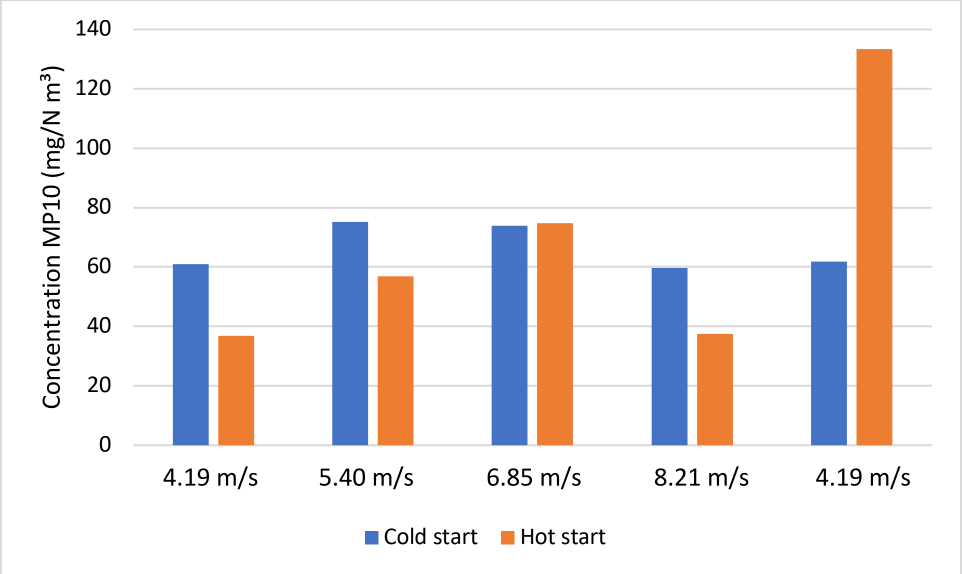
The results found for straw and bagasse are similar to those reported in the literature for sugarcane biomass, where four main degradation events are also reported, which correspond to the main constituents of biomass [38, 39, 40]. For the tested biomass, the maximum degradation peak occurs between 350 - 400 ºC, in this temperature zone an active decomposition area can be considered for its, which is attributed to the degradation of cellulose and hemicellulose, major components of lignocellulosic biomass.

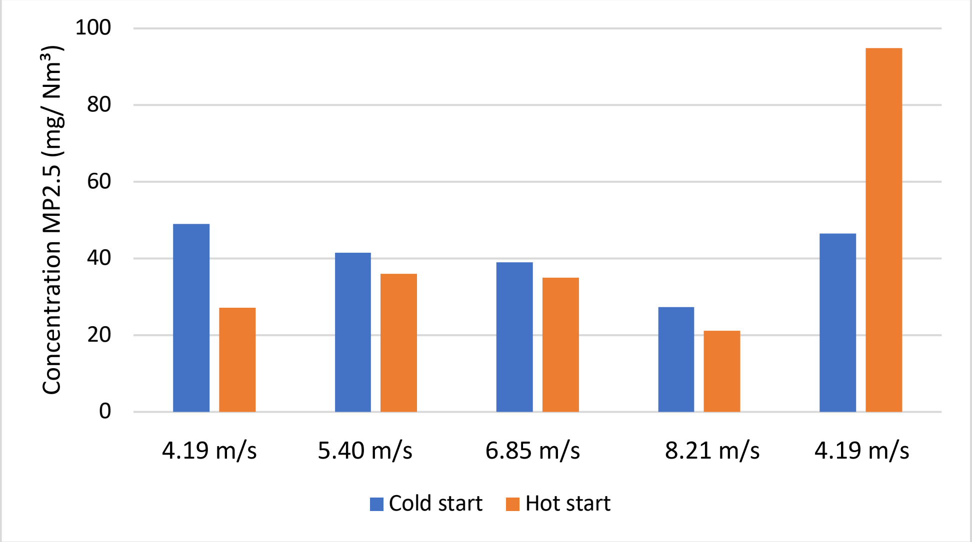
3.2 Combustion test of sugarcane biomass: particulate matter analysis

PM concentration content were calculated for combustion tests with both cold and hot starts, as shown in Fig. 3a for PM_{10} and 3b for $PM_{2.5}$. In general, particulate matter emissions were higher during the experiments with cold start. This is because in these conditions the process temperatures reached inside the combustion chamber are lower. In this case, it results in a lower degree of conversion (oxidation) of the biomass products, which leads to the emission of partially burned chemical compounds [43] and to the emission of larger PM that contribute more actively to the gravimetric results than the micrometric particles.

The behavior of the concentration of emitted particles observed during the combustion tests was a higher concentration for the lower speed range, with an order of 4.19 > 5.40 > 6.85 > 8.21 $m.s^{-1}$. For both fractions PM_{10} (Fig.3 a) e $PM_{2.5}$ (Fig.3 b). This is due to the speed observed inside the duct, behaves like a dragging agent for particulate material, also reflecting in the air flow observed in the chimney during these tests (Table 3). For the tests at the speed of 8.21 m s^{-1} where the flow inside the duct was 0.088 m^3s^{-1}, this behavior is more evident.

Fig.3. Concentration (dry fuel basis) in different speed in the chimney for PM_{10} (a) and $PM_{2.5}$ (b).



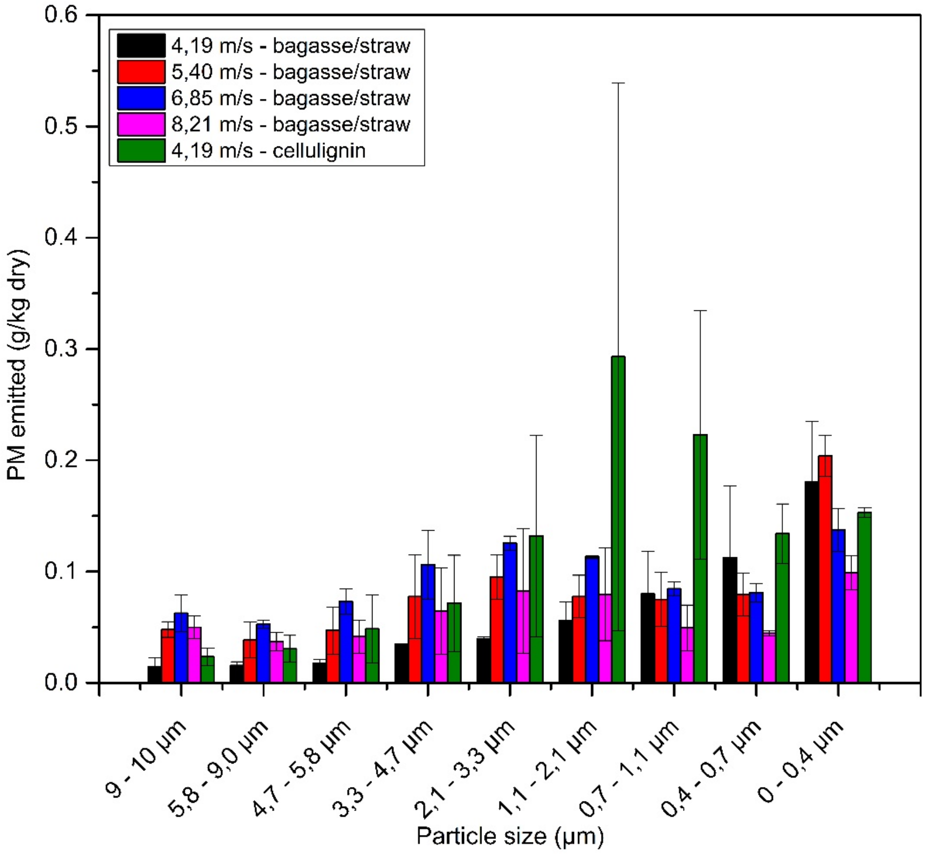


The combustion tests performed with SBP were those that reached the highest average temperatures (Table 3), when compared to the tests performed only with the mixture of straw and sugarcane bagasse under the same conditions (experiments 1 and 2); this is due to the fact that the biomass pre-treated has a higher proportional amount of lignin, this being the fraction responsible for a more intense burning and having a greater calorific power [42, 40], consequently reaching greater temperature ranges due to the combustion quality [12].

The occurrence of intense fire in test 10 (hot start) resulted in a more efficient combustion and with a predominance of the flame phase during sampling. This behavior was reflected in the diameter and concentration of the emitted particles; with a high concentration of $PM_{2.5}$ (Fig.3b).

Fig. 4 indicates PM emissions factor from combustion of 1:1 mixture of straw and sugarcane bagasse and SBP. The emission factor (EF) of PM was defined as the mass of particles emitted per mass of fuel burnt (g kg^{-1}), these values are presented in Table 3.

Fig.4. PM emission factors (FE) dry fuel basis.



Considering the particles corresponding to the fine diameter (<2.5 µm) these were emitted in a higher concentration (Table 3), which is due to the biomass combustion process which results in a higher emission of ultrafine particles [43] in addition the quality and intensity of biomass combustion. The low moisture content of the biomass influences this parameter, a behavior also observed by França *et al.*, (2012).

The highest emissions correspond to the fine diameter (< 2.5 µm) (Fig.4.). However, the present study considers different average speeds observed in the exhaust chimney, which influences the behavior of these particles. Where the speed observed inside the duct behaves as a dragging agent for particulate material.

When considering the tests with the SB, the fraction corresponding to fine particles ($PM_{2.5}$) corresponded in test 1 by the emission of more than 80 % of the total mass fraction, in test 2 more than 70 %, in test 3 to 50 %, in test 4 and test 5 more than 60 %, in test 6 and test 7 more than 45 % and in test 8 more than 55 % of the total mass fraction. Considering SBP, $PM_{2.5}$ corresponded to 75 and 71 % of the total mass fraction for tests 9 and 10; respectively. Other studies that evaluated the emission of particulate matter also reported the emission in high concentration of ultrafine PM [44, 45, 46].

The emission factors obtained for PM_{10} for raw biomass were in the range of 0.414 in test 2 and 0.840 in test 3 and 6. On the other hand, considering the pretreated fraction (SBP) these factors were 0.70 and 1.51, for tests 9 and 10; respectively (Table 3). In the tests carried out with SBP, the average process temperature was higher, with emphasis on test 10; which is related to the active decomposition zone of the studied biomass, between 350 – 400 ºC (Figure 2). In addition, particle collection took place in the flaming phase, that is a greater temperature oxidation process with combustion efficiency because the fire is intense, and the biomass fuel ignites producing large amounts of particles [10].

As a result, a very high standard deviation was observed, even when it comes the same biomass and identical burning conditions; this behavior has also been reported by Kistler [49] and concerns the temperature observed in the bed during combustion.

The emission factors obtained for $PM_{2.5}$ for SB were 0.24 for test 8 and 0.55 for test 1. As for SBP, were 0.53 and 1.08, for tests 9 and 10; respectively.

Table 3. Burn chamber of biomass and emission rates under different operational conditions.

	Air intake (m^3/s)	**MP$_{2.5}$ (mg/m^3)**	**MP$_{10}$ (mg/m^3)**	**FE$_{2.5}$**	**FE$_{10}$**	**Mean temperature (ºC)**	**Mean emission (FE$_{10}$)**
1	0.045	49	61	0.55	0.68	164 ºC	
2	0.045	27	37	0.30	0.41	200 ºC	0.551±0.192
3	0.057	41	75	0.46	0.84	172 ºC	
4	0.057	36	57	0.40	0.64	275 ºC	0.639±0.146
5	0.073	39	74	0.44	0.83	229 ºC	
6	0.073	35	74	0.34	0.84	213 °C	0.840±0.006
7	0.088	27	60	0.30	0.67	219 °C	
8	0.088	21	37	0.24	0.42	228 ºC	0.423±0.177
9	0.045	46	622	0.53	0.70	243 °C	
10	0.045	95	133	1.08	1.51	332 °C	1.514±0.573

Some EFs reported in the literature are in the range of 2.17 - 2.8 g kg^{-1} for combustion tests with sugarcane biomass in open burning tests carried out under laboratory conditions [48, 23]; and burning biomass in the field sampled by aircraft [51]. However, the present experiment and those described by [50] and França [24] even treating with the same biomass, they were carried out under different combustion conditions, such as experimental configuration, combustion temperature, average diameter of the fuel particles, etc. In this sense, the EFs measured in our study (0.41 - 1.51 g kg^{-1} burnt biomass) using a closed system combustion chamber were about 2 times lower than that reported in these studies, where the samples were open burned or in chamber systems that simulate the combustion that takes place in the field.

The tests carried out in closed combustion chambers are more representative and close to this study, it is the case of the experiments of Venkataraman and Rao [26] that evaluated the particulate emissions obtained from the wood burning processes, the experimental unit consisted of a wood stove, and on this a chimney for the collection of exhaust gases. The concentrations of particulate material were obtained from the mass collected from all stages of the cascade impactor (MOUDI). The EFs obtained were 0.8 - 1.8 g kg^{-1} of burnt biomass. Some other authors have also performed tests with a closed-chamber configuration. Gonçalves [52] carried out tests with forest biomass and the obtained EF were 1.12 ± 0.25 (pine) and 2.89 ± 0.90 g kg-1 (golden wattle) of wood burned (dry base). Cereceda-Balic [28] collected particles also in the flame phase and the EFs obtained were 0.65 ± 0.08 g kg^{-1} for *Pinus radiata*, 0.56 ± 0.05 g kg^{-1} for *Eucalyptus globulus* and 0.52 ± 0.03 g kg^{-1} *Nothofagus obliqua*.

Therefore, the results obtained in this work cannot be directly compared, since no similar experiment was carried out using sugarcane biomass. The closest studies are those carried out in a closed chamber, however they are forest biomass, which among all the intrinsic differences of the material, the density can be highlighted, which proved to influence the combustion behavior, where a higher density results in a longer burning time, it is therefore difficult to correlate where each factor will interfere in the combustion process and influence the mass parameters obtained from PM. [51, 26].

The observed differences in FE can be related mainly to the intrinsic characteristics of the biomass used, such as the particle size of the combustible material, density, humidity, experimental unit, dilution techniques used, variations in inlet and outlet air; and other differences in the firing and sampling procedures [13, 41, 52].

3.3 Emission factors of ions

Table 7 displays the EFs of water-soluble ions in PM2.5. The PM2.5 mass the emissions are enriched in Cl$^-$ and K; these results are similar to sugarcane emission outcomes of Mugica-Álvarez [10]. It has been reported that the straw can be burnt together with the bagasse in boilers to fully use the by-products of the sugarcane processing, due to the similar HHV content, however the higher content of chlorine and potassium, coming from the soil, present in the straw tends to resulting in episodes of corrosion and fouling in the boilers.

Table 4. Emission factors of soluble ions in PM2.5 (g kg^{-1} dry fuel) from sugarcane burning.

Water soluble ions	EF (g kg^{-1})
K^+	1.01
Cl^-	4.99
NO^{3-}	1.16
$C_2O_4^{2-}$	0.79
SO_4^{2-}	0.70
NH_4^+	0.02

The main ions emitted were K^+, Cl^-, NO^{2-} e $C_2O_4^{2-}$ which are characteristic of biomass combustion processes. Potassium is used as a biomass burning tracer and presented a significant emission in practically all diameter ranges evaluated. [53, 26, 54].

Chloride ion content varies with biomass species, proximity to the sea, intensity of fertilizer uses and soil leaching. The inorganic fraction present in burning aerosols represents less than 10%, the remainder being composed of organic constituents; but since they are active species, it is important to identify and measure them [57]. The abundance of the fraction corresponding to cations and anions is related to the type of biomass, combustion conditions and even the type of soil that the agricultural crop was cultivated [58].

4 Conclusion

The biomass burning experiment using the closed-system combustion chamber was performed. The EFs of PM from the burning of the pre-treated biomass it was higher when compared to untreated biomass, which is mainly due to the higher temperature of the process due to the higher HHV of this material; caused by the removal of hemicellulose and a proportional increase in lignin.

Thus, the use of a pre-treatment step in the biomass to obtain a hemicellulosic hydrolysate results in a solid fraction with higher HHV, thus resulting in a more intense burning process and consequent higher FE.

It is desirable to determine precise emission factors for the development of inventories and apportionment of sources. However, the wide variety of biomass burning installations reported in the literature shows a variable range of FE that directly depend on the dilution used, which prevents saturation of the sampling equipment in addition to the gaseous flux flow in the chimney, obtained during the period of sampling.

This study presented the emission factors of particles emitted during the combustion of sugarcane biomass and its pre-treated fraction. These data are important for investigating the particles emitted through a common process that takes place in countries that have this crop as the main energy biomass available. There is a need to establish parameters that allow for more homogeneous data, thus aiming to provide an inventory of these particles, since these are useful resources for the management of air quality, in addition to strategies aimed at controlling them, especially of particles ultra-fines that are more harmful to health and persist in the atmosphere for longer and can travel long distances.

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Compliance with Ethical Standards

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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