Evaluation of the efficiency of a Venturi scrubber in particulate matter collection smaller than 2.5 µm emitted by biomass burning

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Abstract
Energy demand has increased worldwide, and biomass burning is one of the solutions most used by industries, especially in countries that have a great potential in agriculture, such as Brazil. However, these energy sources generate pollutants, consisting of particulate matter (PM) with a complex chemical composition, such as sugarcane bagasse (SB) burning. Controlling these emissions is necessary; therefore, the aim was to evaluate PM collection using a rectangular Venturi scrubber (RVS), and its effects on the composition of the PM emitted. Considering the appropriate use of biomass as an industrial fuel and the emerging need for a technique capable of efficiently removing pollutants from biomass burning, this study shows the control of emissions as an innovation in a situation such as the industrial one with the use of a Venturi scrubber in fine particle collection, in addition to using portable and representative isokinetic sampling equipment of these particles. The pilot-scale simulation of the biomass burning process, the representative sampling of fine particles and obtaining parameters to control pollutant emissions for a Venturi scrubber, meets the current situation of concern about air quality. The average collection efficiency values were 96.6% for PM>2.5, 85.5% for PM1.0–2.5, and 66.9% for PM<1.0. The ionic analysis for PM<1.0 filters showed potassium, chloride, nitrate, and nitrite at concentrations ranging from 20.12 to 36.5 μg/m³. As the ethanol and sugar plants will continue to generate electricity with sugarcane bagasse burning, emission control technologies and cost-effective and efficient portable samplers are needed to monitor particulate materials and improve current gas cleaning equipment projects.

Keywords Particulate matter · Venturi scrubber · Biomass · Control · Air pollution · Clean emission

Introduction
Population growth and increasing global energy demand have stimulated the development and search for new renewable energy sources. The emerging use of bioenergy in multiple countries has opened up an international debate on the environmental impacts related to this practice such as deforestation, biodiversity loss, and population health issues caused by water and air pollution (Roy et al. 2020). Industrial companies, in general, are seeking an economic alternative to their fuels, providing technical, economic, and environmental benefits, and the total or partial substitution of fossil fuels using biomass has shown evidence of this improvement. In Brazil, sugarcane bagasse is bioenergy input. Sugarcane bagasse is defined as the solid remaining from sugarcane juice extraction in the milling stage and predominantly comprises carbon and oxygen. Due to its abundant availability and high calorific value, sugarcane bagasse

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has been widely used to generate electric energy through combustion processes in Brazil (Dantas et al. 2013; Furtado Júnior et al. 2020; Sthel et al. 2019).

Moreover, sugarcane bagasse burning is of great importance in the sugar and alcohol industry. In energy cogeneration plants, biomass combustion is used to meet industrial energy demands and the energy surplus is sold to concessionaires. This practice is necessary for the economic viability of these industrial processes, and as an alternative to energy sources from fossil fuels (Carvalho et al. 2019; Cavalcanti et al. 2020; Contreras-Lisperguer et al. 2018; Gongora and Villafranco 2018). In addition, the energy recovery by burning this biomass was higher when compared to gasification or anaerobic digestion (Mohammadi et al. 2020; Stanmore 2010).

One of the drawbacks of thermolectric energy generation methods is the high rate of pollutant emission into the atmosphere. Specially in small-scale thermolectric plants when combined to a lower technological development, the increased emission of fine particulate matter (PM) is a common issue (Bianchini et al. 2018). Generally, the furnace of thermolectric plants uses temperatures between 1443 and 1496 K to burn sugarcane bagasse. At this temperature range, sugarcane bagasse combustion emits a large amount of pollutants that are released directly into the atmosphere, which is a serious environmental problem (Salinas et al. 2020). The combustion vapor emitted by the furnace contains an enormous amount of inorganic ions (NO$_3^-$, SO$_4^{2-}$, NH$_4^+$, K$^+$), PM, and volatile organic compounds (benzene, levoglucosan), among others. These compounds, if emitted into the atmosphere or accumulated in enclosed spaces, impact both the environment and the health of those operating the burning equipment (Sharma and Mandal 2017; Urban et al. 2016).

In contrast to the energy benefits, the burning of biomass emits greenhouse gases and fine particulate matter (PM), which impact the climate and human health. Thus, it is evident that there is an urgent need to reduce PM and gas concentrations from industrial processes that use biomass as an energy source, which is abundant, for example, in sugar and alcohol industries. In this context, industrial collection equipment is needed, which can reduce the emission of pollutants and be adapted according to the type of biomass and combustion characteristics. The most indicated harvesting equipment is gas scrubbers, which can be found in most companies in the sector.

Cieslinski et al. (2015) and Samae et al. (2021) showed sample results of PM from burning sugarcane bagasse, for PM$_{2.5}$ and PM$_{10}$ respectively. For diameter ranges between 1 and 2.5 μm, PM concentrations of (3.94 ± 0.12) g/kg were found. In this context, Costa et al. (2018) and Sthel et al. (2019) concluded that burning biomass for energy is a mitigating measure for environmental impacts, as it reduces CO$_2$ compared to burning fossil fuel, but has several other impacts. Exposure to pollutant particles smaller than 2.5 μm in the biomass burning process is related to health impacts in the population exposed to this pollution, such as an increased risk of infections and cardiorespiratory diseases. A vast body of research has observed a relationship between the amount of hospital admissions and consultations related to the concentration and diameters of particulate pollutants in the air (Chang et al. 2020; Heinzlerling et al. 2016; Krall et al. 2017; Machin et al. 2019; Saleh et al. 2020; Zhao et al. 2021a). Recent studies show the harmful effects of PM emission by biomass burning on populational health in various geographical areas. Populations exposed to fire smoke pollution are more prone to developing respiratory problems, morbidity, and possibly cardiovascular health issues (Mueller et al. 2020; Reid et al. 2016).

Furthermore, in the context of the pandemic due to coronavirus disease, higher concentrations of 2.5 μm particles have been associated with more cases of infection, more complicated cases of infection, and more fatal cases of the disease (Kutralam-Muniasamy et al. 2021; Lorenzo et al. 2021; Marquès and Domingo 2022). Several other studies have evaluated the influence of PM$_{2.5}$ on human health, linking its effects to increases in the risk of hemorrhagic stroke (Zhao et al. 2021b), hospitalizations due to heart failure (Li et al. 2021), hospital readmissions for schizophrenia (Ji et al. 2021), risk of platelet elevation (Hehua et al. 2021), and loss of life expectancy (Zheng et al. 2021). Another important factor to be considered is the composition of this PM. Ferreira et al. (2016) observed the composition of PM and the types of diseases associated with the elderly. For PM$_{2.5}$, they observed that higher concentrations of SO$_4^{2-}$ and NH$_4^+$ were related to a higher risk of circulatory diseases. For PM$_{2.5-10}$, there was a relationship between respiratory diseases and SO$_4^{2-}$, and for circulation diseases, SO$_4^{2-}$, NO$_3^-$, and K$^+$ were related.

In studies carried out by Fang et al. (2019) on PM composition, carcinogenic compounds were found, and they were associated with industrial production. The authors concluded that there is a need to reduce the emitted concentrations of PM from industrial processes for the safety of human health. The emission of atmospheric pollutants by the biomass burning process is a matter of concern. Therefore, developing equipment able to collect pollutants emitted by combustion processes is of the utmost importance. Collection equipment is generally used to control pollutant emission into the atmosphere and can be adapted according to the type of biomass and combustion characteristics (Bianchini et al. 2018; Maduna and Tomašić 2017). Relevant technologies applied in emission control are cyclones, sieve filters, precipitators, and scrubbers. The most suitable equipment to be applied in combustion pollution control depends on economic and technical efficiency studies, properties of the
pollutants, and compliance with local current legislation requirements. In the alcohol and sugar industries, gas scrubbers, also known as scrubbers, can be mentioned as pollution control technology. Scrubbers remove pollutants by spraying liquid inside the equipment (Mardones and Saavedra 2016; Volchyn et al. 2018).

The Venturi scrubber is equipment for fine PM widely used in chemical, ore, timber, cellulose and paper, rock, and solid waste incinerator industries. The Venturi scrubber has some advantages, such as good cost benefits, as it is compact, has high efficiency for fine (PM1.0) and ultrafine particles (PM2.5), and versatility, enabling operation with gases at high temperatures, as well as sticky and explosive particles. Furthermore, this technology is able to reuse the liquid effluent generated in the washing process (Bianchini et al. 2016; Moran 2017).

The liquid to gas ratio in a Venturi scrubber is a process parameter that directly influences the collection efficiency and the economy of this natural resource. Collection efficiencies can be associated with different design variables and phenomena that occur within the throat, such as scrubber geometry, throat length, the ratio between liquid and gas flow, jet penetration, liquid film fraction, droplet distribution, and the diameter of the droplets formed, which are important parameters for the Venturi scrubber (Costa et al. 2005, 2004; Guerra et al. 2017). Lima et al. (2017) studied the influence of the number of orifices, the gas velocity at the throat, and the liquid-to-gas ratio on liquid film formation in two Venturi scrubbers, in the vertical position, of circular section of 20 mm and 40 mm throats. The study then concluded that the greater the number of the orifices, the lower the penetration of the liquid jet into the interior of the throat, thus increasing the adhesion of liquid on the walls of the equipment.

Venturi scrubbers are a preferred design when the required collection efficiency should be higher than between 70 and 99% for particles of 1 µm aerodynamic diameter or smaller (Calvert et al. 1972; Costa et al. 2005; He et al. 2017; Mardones and Saavedra 2016). The washer fluid, usually water, is injected into the throat section of the Venturi scrubber in different ways. When the washer fluid penetrates the Venturi throat, the kinetic energy (high gas velocity) causes the injected liquid to be atomized, thus taking the form of drops that can vary in size from 10 to 500 µm. The resulting drops are dragged and accelerated by the gas. When pollutant particles are in contact with the droplets, the particles are collected by the mechanisms of inertial impaction, direct interception and Brownian diffusion (Maduna and Tomašić 2017; Volchyn et al. 2018; Yamile et al. 2021). The efficiency of a Venturi scrubber depends mainly on the liquid/gas ratio (ratio between the flow of injected liquid and the flow of gas that reaches the throat), length of the throat and speed of the gas inside the equipment (Bianchini et al. 2016, 2018; Costa et al. 2005; Yamile et al. 2021).

Bianchini et al. (2016) compared the 2.5 µm PM efficiency of different cleaning systems tested from corn combustion in a 25-kW boiler. They even evaluated a Venturi scrubber with a bubble column to increase the collection efficiency to values above 90%. For tests where all the fans were turned off, where the water column reached 250 mm, the efficiency was 89.75% and the PM concentration in the outlet gases was 20 mg/m³. Another test, in which the fans were turned on and where the water column reached 360 mm, the removal of PM1.0 increased to 94.77% and the PM emission decreased to 10 mg/m³. Ali et al. (2013) used hydrophobic particles of TiO2 with a diameter of 1 µm and a density of 4.23 g/cm³ and the Venturi scrubber operated at gas mass flow rates of 0.09, 0.115, and 0.14 kg/s and liquid mass flow rates of 0.1, 0.13, and 0.16 kg/s. Overall collection efficiencies ranged from 91 to 98%.

Considering the appropriate use of biomass as an industrial fuel and the emerging need for a technique capable of efficiently removing pollutants from biomass burning, this study shows as an innovation the control of emissions in a situation similar to the industrial one with the use of a Venturi scrubber in the collection of fine particles, in addition to the use of a portable and representative isokinetic sampling equipment of these particles. The pilot-scale simulation of the biomass burning process, the representative sampling of fine particles and obtaining parameters for the control of pollutant emissions to a Venturi scrubber, meets the current situation of concern about air quality. Thus, a closed burning chamber was used to simulate industrial biomass burning, with and without a collection equipment. The PM concentration and size distribution, emitted during the burning, chemical analyses, and SEM images of the PM retained on the filters were analyzed using two samplers to validate the new portable isokinetic sampler. Since the ethanol and sugar plants will continue to generate electricity with sugarcane bagasse burning, emission control technologies and cost-effective and efficient portable samplers are needed to monitor particulate materials and improve current gas cleaning equipment projects.

Materials and methods

Fuel

The sugarcane bagasse and straw used as fuel was provided by the Santa Cruz Sugar and Alcohol Plant of the San Martinho Group—SP. The biomass was grounded and naturally dried (outdoors) to remove water, reaching a final humidity of around 7%. The material was stored in bags to be used in the
combustion tests. This fuel was characterized according to its elemental and immediate composition.

**Rectangular Venturi scrubber and burner system**

The biomass burning and collection systems comprising the Venturi scrubber and cyclone, to separate the liquid droplets, can be seen in Figs. S1 and S2. The sugarcane bagasse was fed through a worm screw to the combustion chamber. In the chamber, the combustion process of the material takes place, where the primary air is induced by a fan and the flow rate is controlled and quantified. The combustion process reaches the regime and remains continuous during the experiments. An average of 6 kg of feedstock was used for each firing test. The pipes used for PM sampling are located upstream and downstream of the Venturi scrubber Pitot tubes and thermometers were used to characterize fluid flow inside the burner. The piping upstream of the scrubber had rectangular dimensions, while the piping downstream of the scrubber had circular dimensions, as shown in Table 1. The gaseous flow with the pollutants from the combustion was directed by blowers followed by two exhaust fans. These directed all the gaseous flow and the PM to the main duct in which the Venturi scrubber was fixed, reaching a maximum velocity at the scrubber throat. The Venturi scrubber used has 4 water injector nozzles positioned in the throat. The Venturi scrubber, located between the burner and the cyclone, has a rectangular geometry. Table 2 shows the dimensions of the Venturi scrubber used. Water was used as the washing liquid.

The gas stream would collide with water jets coming from the washer injector nozzles. The jets were atomized by the high velocity of the gas flow (70 to 150 m/s). The PM was collected by liquid drops, forming liquid agglomerates that were later separated from the gases by a cyclone, where the clean and cooled gases exited at the top of the equipment and the particles with water followed the conical part of the cyclone and were directed to the liquid collection box. These liquid effluents went through chemical decantation, separating the liquid and the coal sludge. To evaluate the efficiency of the Venturi scrubber, tests were performed with different gas velocities at the throat. For each speed, the flow rates of water injected into the scrubber were evaluated, ranging from 2.5 to 6.0 L/min. Regarding the gas velocity at the throat, five different velocities were used, each one related to a frequency of the compressors that drove the gas mixture into the Venturi scrubber. Tables 3 and 4 show, besides the parameters mentioned, other important variables for the development of the tests.

### Table 1 Dimensions of the PM sampling ducts

| Pipeline upstream of the Venturi |    |
|---------------------------------|----|
| External width (cm)             | 6.0|
| External height (cm)            | 4.0|
| Thickness (cm)                  | 0.5|
| Internal width (cm)             | 5.0|
| Internal height (cm)            | 3.0|
| Pipe cross sectional area (cm²) | 15.0|
| Piping downstream of the Venturi|    |
| Internal diameter (cm)          | 12.4|
| Section area (cm²)              | 120.6|

### Table 2 Dimensions of the throat, convergent, and divergent section of the Venturi scrubber

| Parameter                  | Value       |
|----------------------------|-------------|
| Throat length (Lth)        | 11.7 cm     |
| Throat width (Wth)         | 2.4 cm      |
| Throat height (Hth)        | 3.5 cm      |
| Divergent length (Ldiv)    | 28 cm       |

### Table 3 Test operating conditions

| Parameter                  | Value       |
|----------------------------|-------------|
| Installed burner power     | 8.1 kW (11 CV) |
| Water flow rate            | 2.5 L/min e 6.0 L/min |
| Biomass feed flow          | 18 kg/h     |
| Air flow for combustion    | 125 m³/h    |
| Biomass burnt per test     | 6 kg        |
| Gas velocity at the throat (Vth) | 88, 137, 174, 217 e 262 m/s |
| Liquid/gas ratio           | 0.2 – 1.4 L/m³ |
| Number of orifices in Venturi | 4           |
| Sampling time              | 20 min (isokinetic sampler) |
|                           | 5 min (cascade impactor) |

### Table 4 Gas velocities at the Venturi scrubber inlet, throat, and outlet pipes

| Venturi frequency (Hz) | V_inlet (m/s) | V_outlet (m/s) | V_th (m/s) |
|------------------------|--------------|---------------|-----------|
| 20                     | 49.3         | 3.4           | 88.1      |
| 30                     | 76.6         | 5.8           | 136.9     |
| 40                     | 97.3         | 6.0           | 173.9     |
| 50                     | 121.3        | 8.8           | 216.8     |
| 60                     | 146.8        | 10.3          | 262.4     |
Particulate matter sampling

The isokinetic sampling process was carried out under conditions indicated by the norms that guide a representative of PM sampling. Sampling was carried out at multiple points inside the duct and the British standard BS 3405:1983 was used. In PM sampling smaller than 10 μm, two samplers were used: a new portable isokinetic sampler and an Andersen cascade impactor. Sampling was performed by positioning portable isokinetic samplers before and after the Venturi scrubber simultaneously, in addition to sampling the smoke plume using an eight-stage Andersen cascade impactor. In this sampler, the PM is classified by a varying size range from 0 to 10 μm. The Andersen cascade impactor stages were (μm): S1 (PM<0.4), S2 (PM0.4–0.7), S3 (PM0.7–1.1), S4 (PM1.1–2.1), S5 (PM2.1–3.3), S6 (PM3.3–4.7), S7 (PM4.7–5.8), S8 (PM5.8–9.0), and backup (PM9.0–10). The cascade impactor was positioned vertically in the smoke plume in the exhaust stack. The new portable isokinetic sampler collected PM in three bands of diameter (μm): B1 (PM>2.5), B2 (PM2.5–1.0) and B3 (PM<1.0) (Fig. S3). This new sampler consisted of three circular filter holders to retain particles larger than 2.5 μm, with sizes between 2.5 and 1.0 μm and smaller than 1.0 μm. The filters used in both PM samplers were fiberglass filters. All the filters were previously dried in an oven at 105 °C and taken for gravimetric analysis when their weight was found to be constant. The fiberglass filters were weighed on an analytical scale with an accuracy ±1 μg, packaged and identified. After PM collection, the same procedure was performed with the used filters for the gravimetric analysis.

The sampling system consisted of isokinetic probes and nozzles, suction pumps, needle valves and flowmeters to collect PM in the isokinetic pipelines of the equipment. Sampling was conducted for 20 min after the fuel burning process reached the established regime. The isokinetic samplers acted simultaneously in the PM collection placed downstream and upstream of the Venturi scrubber in all tests. The temperature profile of the gases was recorded and ranged from 150 to 350 °C. The temperature in the combustion chamber exceeded 900 °C.

Soluble ion extraction and chromatographic analysis

After PM collection, the same procedure was performed for gravimetric analysis. The PM retained on the sampler filters after weighing was submitted to analytical methods to determine the water-soluble ions. The fiberglass filters present in each sampler stage of the cascade impactor were cut into pieces of 4 cm² to facilitate the extraction of soluble ions present in the PM. The filter pieces were inserted into a falcon tube and Milli-Q Millipore deionized water was added to solubilize the ions present in the PM sampled in the atmosphere and by a fixed source. This solution was submitted to mechanical shaking for 40 min to solubilize the ionic species. After mechanical agitation, the resulting solutions were filtered by a hydrolyzed membrane (Millipore) Millex-HV with a pore size of 0.45 μm used to retain material larger than the membrane pores. Approximately 1.5 mL of the filtrate was transferred to a vial for chromatographic analysis. An ion chromatograph (Thermo Scientific) model ICS 5000 analytical was used to determine water-soluble ions in the PM. The analyzed species were anions (fluoride (F−), acetate (HCH3COO−), formate (HCOO−), chloride (Cl−), nitrite (NO2−), nitrate (NO3−), sulfate (SO42−), oxalate (C2O42−), phosphate (PO43−), and cations (sodium (Na+), ammonium (NH4+), potassium (K+), magnesium (Mg2+), and calcium (Ca2+)). Blank filters were also collected and analyzed to examine possible contamination. The analyses were performed in a DIONEX ion chromatograph, model DX-120, with an IonPac AS14 4 mm column for anions and CS 12A 4 mm for cations, containing a conductivity detector and a self-regeneration suppressor. The eluents used were 12 mM H2SO4 for cations and 5 mM Na2CO3/NaHCO3 1.0 mM for the anions.

Particulate matter collection efficiency

The efficiency of the Venturi scrubber collecting pollutants from the flue gases is estimated in Eq. (1), in which \( C_{1,S} \) is the concentration of pollutants leaving the scrubber and \( C_{i,E} \) is the concentration of pollutants entering the Venturi scrubber.

\[
E_i = \frac{C_{i,E} - C_{i,S}}{C_{i,E}} \tag{1}
\]

The PM concentrations (kg/m³) were measured before and after the Venturi scrubber and were calculated according to Eq. (2).

\[
C_i = \frac{m_i}{V} \tag{2}
\]

The mass \( m_i \) (kg) of PM was measured by the difference of weight of the fiberglass filters before and after the sampling tests. The sampled volume \( V \) (m³) was measured according to the sampling flow rate and the duration of the tests.

Scanning electron microscope analysis

Imaging tests and particle counts were performed to evaluate the sampling process with the new portable isokinetic sampler. The new filters (unused) and the filters from the three stages of the isokinetic sampler (B1, B2, and B3) for
both sampling points (before and after the Venturi scrubber) were analyzed. Two different regions of each filter (the central part and one point more distant from the center) were analyzed using a scanning electron microscope (JSM-7500F, Jeol, Japan and Software PC-SEM Ver 2.1.0.3). The average particle diameter was determined by a method that measures the greatest distance, edge to edge, particles observed by SEM images, using the counting Software Image J 1.52i (64-bit). All samples were metalized with carbon one wire (~11.4 nm coating, which was already discounted from the average diameters found for the particles). The elemental compositions of the filters were determined by EDS analysis using a voltage acceleration of 5.0 keV and a live time of 5 min, using a Thermo Fisher Scientific Ultra Dry detector attached to the SEM-FEG. Areas were chosen at random to examine the elements present in each filter.

**Results and discussion**

**Fuel characteristics**

The moisture content of the biomass was 7.71% for the straw and bagasse mixture. Biomass-based fuels used in thermochemical processes must have humidity values below 10% as a higher water content makes the process energetically unfavorable and reduces the biomass thermal conversion efficiency. According to Setter et al. (2020), biomass with a low percentage of oxygen and a high carbon content is advantageous to be applied in power generation purposes. The results of the elementary and immediate composition of straw and bagasse mixture, before and after the combustion test, can be seen in Table 5.

Carbon and hydrogen are important elements for heat release during the burning process. The composition obtained for the bagasse presented in Table 5 is very close to that presented by Demirbas (2004) and Cardoso et al. (2019). Low values of S and N content lead to lower SOx and NOx emissions during biomass burning processes, while high C and H contents contribute positively to the calorific value due to CO, CH4, and H2 conversion (Gautam and Chaurasia 2020). According to Khiari et al. (2019), biomasses with a nitrogen content below 10% do not contribute significantly to NOx production during the thermal degradation process.

The calorific value represents the amount of energy released from a fuel during its complete combustion, and its determination is important to evaluate its use as a fuel. The calorific value found in this study is comparable to the results obtained by other authors, who reported calorific values for sugarcane processing waste of 16.42 MJ/kg (Ferreira et al. 2016) and 17.02 MJ/kg (Lee et al. 2013).

**Particulate matter emissions by sugarcane bagasse and straw burning**

Biomass burning emits a high concentration of particles smaller than 2.5 μm. For the samplings carried out with both samplers, it was found that the biomass burning, in fact, emits higher concentrations of fine and ultrafine particles, the most harmful to the environment and human health. Figure 1 shows the average concentrations of PM, in μg/m3, emitted and sampled by the Andersen cascade impactor and the new portable isokinetic sampler, respectively. These

| Properties                      | Bagasse and straw mixture | Combustion material in gas chamber | Combustion material in chamber |
|---------------------------------|---------------------------|------------------------------------|--------------------------------|
| Elemental analysis (%)          |                           |                                    |                                |
| Carbon (C)                      | 42.69                     | 41.48                              | 0.31                           |
| Hydrogen (H)                    | 5.38                      | 2.07                               | 0.70                           |
| Nitrogen (N)                    | 0.80                      | 1.80                               | 0.77                           |
| Oxygen (O)                      | 37.18                     | 13.02                              | 0.00                           |
| Sulfur (S)                      | 1.18                      | 0.56                               | 0.09                           |
| H/C                             | 0.13                      | 0.05                               | 2.26                           |
| O/C                             | 0.87                      | 0.31                               | 0.00                           |
| Immediate analysis              |                           |                                    |                                |
| Moisture (%)                    | 7.71 ± 0.32               | –                                  | –                              |
| Volatiles (%)                   | 84.22 ± 1.41              | –                                  | –                              |
| Fixed carbon (%)                | 11.34 ± 1.68              | –                                  | –                              |
| Ash (%)                         | 4.41 ± 0.38               | –                                  | –                              |
| LHV* (MJ/kg)                    | 15.91                     | 14.84                              | 0.29                           |
| HCV** (MJ/kg)                   | 18.58                     | 16.90                              | 2.45                           |

LHV*, lower heating value; HCV**, higher calorific value
In Fig. 1a, analyzing the PM range between 0.0 and 0.4 μm (S8) of the Andersen cascade impactor, the condition that used $V_{th} = 137$ m/s emitted the highest PM. The conditions that used $V_{th}$ of 137 m/s, 174 m/s, and 217 m/s were the conditions that emitted the maximum values of PM concentrations in the S8 (0.0–0.4 μm), 16,027 μg/m³, 12,720 μg/m³, and 10,376 μg/m³, respectively, which were at least 14% of the total emitted in each test.

Nevertheless, the results obtained from the isokinetic portable sampler with $V_{th} = 137$ m/s, $V_{th} = 217$ m/s and $V_{th} = 262$ m/s (Fig. 1b) were the ones with the highest concentration values, considering the PM range of less than 1.0 μm (B3), representing more than 40% of the total emitted in each test, with values of 26,235 μg/m³, 23,556 μg/m³, and 42,400 μg/m³, respectively.

Variations in the individual tests may indicate a change in the combustion process, entrainment of larger particles by the high gas velocity, and variation in fuel characteristics. Hu et al. (2020) obtained PM$_{10-1.0}$ concentrations between 23,000 and 85,000 μg/m³ for burning two types of wood bark mixture in a 30-MW biomass burning plant. Biomass burning emits higher concentrations of fine and ultrafine particles, which are the most harmful to the environment and human health. In addition to the high PM concentrations in the diameter range of 0.0–0.4 μm (S8), the ranges 3.3–4.7 μm (S4) to 1.1–2.1 μm (S6) also showed high emission concentrations.

For each of the velocities, a tendency of growth in the PM concentration was generally observed at higher gas temperatures in the duct. For these temperature values, the flame phase of the combustion process is more intense, leading to more efficient combustion of the biomass. Table 6 shows the
PM emission rates for the 2.5 µm (S5 to the backup stage) and 10 µm (S1 to the backup stage) diameter range and the average combustion gas temperature inside the duct.

For the condition of $V_{th} = 217$ m/s and combustion gas temperatures of 132 and 229 °C, the PM concentration increased by 140%. On the other hand, by increasing the $V_{th}$ from 217 to 262 m/s, keeping the gas temperature at approximately 229 °C, the PM concentration was a decrease of $-84.9\%$. Thus, with higher temperature values in the combustion process, the concentration of fine particles increases. However, due to an increase in gas flow, for the same temperature range, the concentration of particles is diluted.

It was also observed that the PM concentration below 1.0 µm was predominant in high gas temperature flares due to the quality of the combustion in these conditions. Some emission factors (EFs) reported in the literature are in the range of 2.17–2.8 g/kg for combustion tests with sugarcane biomass, in open burning tests carried out in laboratory conditions (Christian et al. 2007; França et al. 2012). The different phases of combustion emit pollutants in different diameter ranges; the more intense fire (flame phase) results in particles of smaller diameters and in higher concentrations, whereas combustion that reaches lower temperatures, results in particles of larger diameters (Hall et al. 2012).

Table 7 shows the emission factors and PM emissions observed in the isokinetic sampler, to the average temperatures of the gases in the duct at each of the gas velocities at the throat. For each value of the gas velocity evaluated, there was an increase in the PM concentration emitted with the increase in the burning temperature, especially for sampled particles smaller than 1.0 micron.

### Table 6 PM emissions observed in the Andersen cascade impactor, for each diameter range, according to the combustion gas temperatures

| Throat gas velocity (m/s) | Combustion gas temperature (°C) | $E_{2.5}$ (gPM/kg biomass) | $E_{1.0}$ (gPM/kg biomass) | Particulate concentration (µg/m³) |
|--------------------------|---------------------------------|-----------------------------|-----------------------------|---------------------------------|
|                           |                                 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | Backup |
| 88                       | 173.0                           | 21 | 0.21 | 0.08 | 3147 | 3733 | 6080 | 10,773 | 7093 | 6080 | 3467 | 3680 | 6667 |
| 137                      | 164.3                           | 47 | 0.47 | 0.37 | 1760 | 1600 | 1813 | 3147 | 3627 | 6027 | 9493 | 14,027 | 19,467 |
| 199.9                    | 60.21                           | 28 | 0.28 | 0.21 | 800 | 1120 | 1333 | 3040 | 3360 | 3947 | 4693 | 5920 | 12,587 |
| 174                      | 172.3                           | 60 | 0.60 | 0.33 | 4747 | 4480 | 5547 | 9280 | 9653 | 8053 | 8213 | 8267 | 17,013 |
| 187.7                    | 0.24                           | 24 | 0.24 | 0.11 | 11,307 | 800 | 1227 | 1280 | 2240 | 3573 | 2507 | 2987 | 4587 |
| 234.4                    | 0.30                           | 30 | 0.30 | 0.17 | 2667 | 3733 | 3573 | 2667 | 2987 | 4000 | 2560 | 4960 | 9973 |
| 274.8                    | 0.45                           | 45 | 0.45 | 0.29 | 3840 | 2400 | 2880 | 4533 | 7200 | 5653 | 5120 | 5867 | 19,307 |
| 217                      | 132.0                           | 78 | 0.78 | 0.48 | 1625 | 1060 | 1802 | 3463 | 5053 | 4276 | 3180 | 3569 | 9611 |
| 177.9                    | 0.34                           | 34 | 0.34 | 0.22 | 2133 | 1813 | 1387 | 2027 | 2720 | 4800 | 2933 | 3627 | 7413 |
| 213.5                    | 0.87                           | 87 | 0.87 | 0.41 | 6560 | 4427 | 5760 | 11,413 | 11,573 | 10,133 | 7093 | 6667 | 11,040 |
| 229.4                    | 0.86                           | 86 | 0.86 | 0.45 | 4533 | 4907 | 7200 | 7467 | 10,773 | 9920 | 7893 | 7733 | 13,440 |
| 262                      | 219.4                           | 82 | 0.82 | 0.37 | 5067 | 3840 | 4587 | 8160 | 10,827 | 9707 | 5707 | 4053 | 7787 |
| 228.6                    | 0.51                           | 51 | 0.51 | 0.29 | 3840 | 2720 | 2773 | 3253 | 3787 | 4427 | 3093 | 3787 | 9813 |
| 230.9                    | 0.52                           | 52 | 0.52 | 0.28 | 1343 | 1084 | 1107 | 1178 | 1201 | 1413 | 1602 | 1673 | 2026 |

### Table 7 Emission factors and PM emissions observed in the isokinetic sampler, according to combustion gas temperatures

| Throat gas velocity (m/s) | Gas temperature (°C) | $E_{2.5}$ (gPM/kg biomass) | $E_{1.0}$ (gPM/kg biomass) | Particulate concentration (µg/m³) |
|--------------------------|----------------------|-----------------------------|-----------------------------|---------------------------------|
|                           |                      |                             |                             | B1     | B2      | B3    |
|                           |                      |                             |                             | > 2.5 | 1.0–2.5 | < 1.0 |
| 88                       | 197.3                | 0.11                        | 0.08                        | 2097   | 1935   | 4731 |
| 211.5                    | 0.06                 | 0.04                        | 1235                        | 2676 |
| 247.0                    | 0.45                 | 0.29                        | 7233                        | 17,533 |
| 137                      | 197.5                | 0.16                        | 0.10                        | 2100   | 1967   | 3233 |
| 217.5                    | 0.40                 | 0.31                        | 4500                        | 20,000 |
| 231.5                    | 2.39                 | 2.05                        | 29,600                      | 67,000 |
| 174                      | 220.7                | 0.34                        | 0.28                        | 6147   | 1794   | 8765 |
| 245.9                    | 0.26                 | 0.23                        | 14,933                      | 29,067 |
| 217                      | 208.1                | 0.33                        | 0.27                        | 11,333 | 4444   | 23,556 |
| 262                      | 216.1                | 0.73                        | 0.58                        | 27,600 | 10,667 | 42,400 |
In experiments on a laboratory scale of burning sugarcane biomass with a moisture content below 9%, Christian et al. (2007) found EF in the order of 2.17 g of PM2.5/kg of dry biomass burned. Hall et al. (2012) obtained emission factors of 2.49 ± 0.66 g of PM2.5/kg of sugarcane biomass using a burner that simulates the field combustion process. Sanchis et al. (2014) evaluated the emission of PM2.5 from the combustion of rice husks in an open combustion chamber; the material with a moisture content of 5% had EF higher than that observed for sugarcane, around 5.86 ± 1.85 g PM2.5/kg, which is related to the type of biomass used. The different phases of combustion emit pollutants in varying diameter ranges, the most intense fire (flame phase) results in smaller diameter particles and higher concentrations; however, the combustion process at lower temperatures results in larger diameter particles (Hall et al. 2012).

The tests performed in closed combustion chambers are more representative and closer to our study, as the experiments performed the PM collection from the burning of different woods using a controlled combustion chamber. The EF2.5 obtained for the flame phase, which was the same as the one investigated in our study, was 0.65 ± 0.08 g/kg for Pinus radiata, 0.56 ± 0.05 g/kg for Eucalyptus globules, and 0.52 ± 0.03 g/kg for Nothofagus obliqua (Cereceda-Balic et al. 2017). As well as the results obtained from the impactor, isokinetic sampling showed a high emission of ultrafine particles, which are the most harmful to health.

On the other hand, when comparing the PM concentrations of the two samplers, the Andersen cascade impactor and the new isokinetic sampler, for the ranges of > 2.5 µm (S1 to S5 and B1), 1.0–2.5 µm (S6 and B2), and < 1.0 µm (S7 to backup and B3), it can be observed that for concentrations lower than 2.5 µm, the two samplers have similar PM concentrations. Thus, the new isokinetic sampler is able to quantify particulate matter in ranges smaller than 2.5 µm and is a cheap, portable, and easy-to-use option when compared to other PM quantification samplers.

Controlling particulate matter emissions by sugarcane bagasse burning

The concentrations emitted were compared with those of the Venturi scrubber operating (Venturi on) in the cleaning process and not operating. The values can be seen in Fig. 2, which shows the removal efficiencies for each diameter range in the cascade impactor, with Vth = 174 m/s and a water flow rate of 6.0 L/min. The PM retention in several PM diameter ranges can be observed due to the performance of the Venturi scrubber. The tests with VG = 174 m/s and a liquid flow of 6.0 L/min were the most consistent, according to what was expected for the experiment. Particle removal, in the range of 2.0 to 4.7 µm, showed greater efficiency of the Venturi scrubber in collecting PM.
with maximum values of 27.1% for the two ranges, respectively. This reveals the efficiency of the Venturi scrubber in collecting particles above 2.5 µm to the detriment of smaller particles, which are more difficult to collect.

The lower gas velocity in the throat and the flow rate of 6 L/min generated a liquid jet penetration in the central region of the throat, which better distributed the drops inside the throat, increasing efficiency, decreasing the fraction of liquid film on the walls, which does not collect PM. Values of 86% efficiency were achieved for the 0.18–0.32 µm range and 70% for diameters less than 0.056 µm, which were very satisfactory values for such thin diameters. The jet penetration calculation was performed according to Viswanathan et al. (1983), in which 1.75 cm was the ideal penetration value — half of the 3.5 cm height of the throat. The liquid film fraction profile was drawn according to Viswanathan et al. (1997) for calculations.

Figure 4 shows PM emission concentrations in the Venturi on and off, for PM < 1.0 µm (B3) using the isokinetic sampler. The results were expressed as Venturi off (blue) and Venturi on (red), and the sampling was simultaneous, before and after the Venturi scrubber. In this situation, the liquid jet penetration reached 14.4 mm inside the throat, close to the central region, which positively influences the collection efficiency.

When analyzing different $V_{th}$, the Venturi scrubber proved to be efficient in collecting particles less than 1.0 µm. Specifically, for $V_{th} = 137$ m/s, it can be observed that there was a decrease of 29% in PM concentration when compared to the Venturi off condition. It is highlighted that for this diameter range, the collection process at industrial level is complex and hard. Particles smaller than this diameter can deflect from the collecting liquid drops of this equipment. The liquid jet in this experimental condition did not reach the central region of the drop, which was the optimization situation of the scrubber.

Figure 5 shows the results of the collection efficiency of the Venturi scrubber using the isokinetic sampler. The values refer to the average values of the experiments performed.

In this study, we used a liquid/gas ratio of 0.2 to 1.4 L/m³. An optimal performance of the scrubber was found when collecting PM larger than 2.5 (B1) and between 1.0 and 2.5 µm (B2), ranging between 98.4 and 99.6%. Particles larger than 1.0 µm were collected more easily due to their higher inertia, which decreased due to the deflect from the liquid droplets. For fine particulates smaller than 1.0 µm, there was a significant influence on the collection efficiency when increasing the gas velocity at the scrubber throat. After gas velocity was increased, there was more atomization of the water jet at the throat due to an impact, resulting in more liquid droplets available to capture PM.

It was concluded that the experimental condition that includes $V_{th} = 262$ m/s, for a liquid flow rate of 2.5 L/min (liquid/gas ratio equal to 0.19 L/m³), was the best condition for the rectangular Venturi used. The collection efficiencies obtained were influenced by parameters such as a high-water flow rate (2.5 L/min), 4 liquid injection orifices — which increases the distribution of water droplets inside the throat — and high gas velocities.

The efficiencies obtained in this study are within what is expected in the literature, in which the efficiencies for PM greater than 1.0 µm are in the range of 70–90% and PM less than 1.0 µm are around 50%. The highest liquid jet penetration obtained was 0.72 cm, for $V_{th} = 88$ m/s, and the lowest was 0.24 cm, for $V_{th} = 262$ m/s. It was observed that the liquid jet penetration becomes closer to the ideal (1.75 cm) as the gas velocity decreases, consequently increasing the liquid/gas ratio as the water flow rate is constant. This occurred because there was a flattening of the liquid jet as the gas velocity at the throat increased.

In the studies by Bianchini et al. (2016), efficiencies of 60.36% in PM_{2.5} removal were obtained for a water flow rate of 5 L/min, comparable to those obtained in this work. They

![Fig. 4] PM emission concentrations in the Venturi on and off, for PM < 1.0 µm (B3) using the new portable isokinetic sampler

![Fig. 5] Removal efficiencies for each diameter range using the new portable isokinetic sampler. B1 (PM_{>2.5}), B2 (PM_{1.0–2.5}) and B3 (PM_{<1.0})
are higher even than some PM$_{2.5}$ washing systems used by Bianchini et al. (2016), such as the tower wash (28.25%) and the bubble column (58.65%). Mi and Yu (2012) obtained removal efficiencies for the 10 µm and 45 µm particles over 95.1% and 92.7%, respectively, which shows that the collection efficiencies obtained for PM larger than 2.5 µm were notable. Ali et al. (2013) obtained overall collection efficiencies of PM ranging from 95 to 99% for different gas velocities at the throat (130 to 200 m/s).

**Results of chemical analysis on particulate matter retained on the filters**

The results for the ion chromatography analysis of the filters sampled in an isokinetic sampler are shown in Fig. 6 for velocities of $V_{th} = 137$ m/s and $V_{th} = 262$ m/s. The average temperatures obtained in the gas chamber are shown and monitored throughout the test period. The highest potassium, chloride, and nitrate concentrations occurred at the highest burning temperature (231.5 °C), as shown in Fig. 6a. The chemical analysis of water-soluble ions showed that chloride and potassium mass percentages reached 35% and 26% of the total ionic mass, respectively. It was found that the predominant ions, K$^+$, Cl$^-$, and NO$_3^-$, were present in PM at less than 1.0 µm (B3) and lower concentrations of nitrate, magnesium, calcium, sulfate, phosphate, and oxalate. In the B1 and B2, an increase can be observed in the magnesium, calcium, phosphate, and nitrite concentrations (Fig. 6a).

In Fig. 6b, the highest concentration of the species in the different filters of the isokinetic samplers was found for the PM$_{<1.0}$ (B3): potassium, chloride, and nitrate. Potassium, nitrite, and nitrate for PM$_{1.0–2.5}$ (B2). Potassium, calcium, and chloride for PM$_{>2.5}$ (B1).

The predominant emission factors of chloride (Cl$^-$) and potassium (K$^+$), intermediate values for sulfate (SO$_4^{2-}$) and ammonium (NH$_4^+$), and trace amounts of nitrate (NO$_3^-$) and sodium (Na$^+$) were observed in the studies conducted by Chantara et al. (2019) in burning various types of biomasses in an open system combustion chamber. These ions were associated with biomass burning, and the predominance of chloride and potassium was related to the fertilizers and herbicides used in the plantations. Potassium is also a biomass-burning marker. Similarly, studying the impacts of burning on agriculture, NH$_4^+$, K$^+$, Mg$^{2+}$, and HCOO$^-$ and small quantities of Cl$^-$, CH$_3$COO$^-$, Ca$^{2+}$, SO$_4^{2-}$, and NO$_3^-$ were found in the lowest troposphere: dry deposition was associated with the burning periods in the region (Rocha et al. 2005).

Table 8 shows the average concentration values of nitrate, potassium, and sulfate ions in the PM retained in the filters with the Venturi on and off using the Andersen cascade impactor. PM$_{10}$ was the sum of all concentration ions in the nine stages (S1 to backup), and PM$_{2.5}$ was the sum of the six to backup stages.

In Table 8, a decrease in the concentrations of nitrate and sulfate ions was observed for $V_{th} = 217$ and $V_{th} = 137$ m/s, both for PM$_{2.5}$ and PM$_{10}$, when the Venturi scrubber was in operation in the cleaning process. When the Venturi scrubber was in operation and for PM$_{2.5}$, the ionic concentration decreased from 32.4 to 0.1832 for nitrate and from 9.74 to zero for sulfate, respectively. For PM$_{10}$, the decrease was more significant from 34.9 to 0.326 mg/m$^3$ for nitrate and from 15.25 to 1.51 mg/m$^3$ for sulfate. The importance of reducing the concentration of these ions is associated with the trend of increasing cases of circulatory and respiratory diseases in humans, as indicated by Ferreira et al. (2016). Guo et al. (2018) found high emission factors for potassium, chloride, fluoride, and sulfate in the emission of PM$_{2.5}$ from the burning of six main tree species in China. Sillapapiromsuk et al. (2013) also reported higher emission factors for chloride and potassium in PM$_{10}$ determination in a biomass combustion chamber using rice straw, corn residue, and dried leaves.
Table 8 The average concentration values of nitrate, potassium, and sulfate ions in the particulate material retained in the filters with the Venturi on and off in the cleaning process using Andersen Cascade Impactor

| $V_\text{th}$ (m/s) | Venturi operation | Particulate matter (µm) | Nitrate (mg/m$^3$) | Potassium (mg/m$^3$) | Sulfate (mg/m$^3$) |
|-------------------|-------------------|------------------------|-------------------|---------------------|------------------|
| 217               | Off               | PM$_{2.5}$              | 32.4419           | 2.9130              | 9.7376           |
|                   |                   | PM$_{10}$              | 34.3890           | 7.1481              | 15.2574          |
| 137               | Off               | PM$_{2.5}$              | 12.4704           | 10.8626             | 7.5665           |
|                   |                   | PM$_{10}$              | 33.6491           | 22.1459             | 15.5744          |
| 262               | On                | PM$_{2.5}$              | 0.0000            | 10.8266             | 0.0000           |
|                   |                   | PM$_{10}$              | 0.0000            | 11.1447             | 0.0000           |
| 217               | On                | PM$_{2.5}$              | 0.1832            | 18.1000             | 0.0000           |
|                   |                   | PM$_{10}$              | 0.3262            | 18.4542             | 1.5080           |
| 174               | On                | PM$_{2.5}$              | 0.0224            | 6.6860              | 0.0000           |
|                   |                   | PM$_{10}$              | 0.0684            | 6.8908              | 0.0021           |
| 137               | On                | PM$_{2.5}$              | 0.0778            | 15.5065             | 0.01419          |
|                   |                   | PM$_{10}$              | 0.0800            | 15.6979             | 0.01419          |

Fig. 7 SEM images for the isokinetic sampler filters with Venturi off, new filters (left) and B1 filter – PM$_{>2.5}$ (right), at a magnification of (a) 100x, (b) 1500x, and (c) 70,000x
Scanning electron microscopy images and particle counts for portable isokinetic sampler filters

Figure 7 shows an analysis made by SEM for the PM retained in the last filter (B1) and the unused filters at the isokinetic sampler. The filter images confirmed that PM smaller than 1.0 µm are emitted by biomass burn. In Fig. 7b, evidence can be seen of burned plant material (sugarcane bagasse fibers) confirming the incomplete combustion.

In Figs. 8 and 9, the images obtained by SEM for the filters of the three stages of the isokinetic sampler can be observed, both for sampling before the scrubber and the results obtained after collecting the particles by the cleaning equipment.

Table 9 shows the results of the particle counts for PM retained in the isokinetic sampler filters, sampling at the point before and after the Venturi scrubber. The calculated average diameters for the three bands were 36 and 42 nm, before and after the Venturi scrubber, respectively.

It was found that biomass burning emits very fine particles. The average diameters were 41.5 nm, 34.9 nm, and 30 nm for B1 to B3 before the Venturi Scrubber, respectively. Note that the smallest diameters were identified in B3, whose cut diameter was for PM<1.0. These values of diameters emitted by the biomass burning are in agreement with studies found in the literature. In a study carried out by Naydenova et al. (2020), values were observed of particle diameters of 1 µm in the emission of sugarcane bagasse combustion sampled with an optical monitor. The diameters of the collected particles were mostly submicrometers, in the range of 0.1–2.5 µm. For the results sampled in the three stages with the Venturi on, they were 41.8 nm, 41.1 nm, and 42 nm, respectively. In the SEM images (Figs. 8 and 9), spherical particles with even smaller diameters ranging from
9 nm to 14.5 nm can be observed. It should be mentioned that PM emissions from burning biomass are extremely harmful to health considering that they are very small diameters, which are the most difficult to collect in industrial processes. Thus, it is important to design more accessible, economic, and portable collectors to monitor the PM for the gaseous flows and propose alternative gas cleaning equipment to protect human health and reduce adverse environmental effects.

The elementary analysis of the SEM filters identified the following elements Cl, S, and P for the filters used in the collected PM using the isokinetic sampler before and after Fig. 9 SEM images for PM retained in the (a) B1 Filter—PM > 2.5, (b) B2 filter—PM1.0–2.5 and (c) B3 Filter—PM< 1.0, sampling with the Venturi scrubber in operation.

### Table 9

| Parameters | B1 PM> 2.5 | B2 PM1.0–2.5 | B3 PM< 1.0 | B1 PM> 2.5 | B2 PM1.0–2.5 | B3 PM< 1.0 |
|------------|------------|--------------|------------|------------|--------------|------------|
| Number of particles counted | 134 | 139 | 148 | 171 | 153 | 140 |
| D_{10} (nm) | 19.3 | 11.7 | 9.1 | 14.5 | 11.9 | 13.7 |
| D_{50} (nm) | 34.6 | 20.8 | 24.1 | 33.8 | 33.4 | 35.2 |
| D_{90} (nm) | 1.4 | 60.4 | 45.7 | 66.1 | 65.7 | 65.2 |
| Average diameter (nm)* | 41.5 ± 2.8 | 34.9 ± 3.2 | 30.0 ± 2.3 | 41.8 ± 2.8 | 41.1 ± 3.1 | 42.0 ± 3.2 |

* Confidence Interval = 95%
the Venturi scrubber (Fig. S4). These elements differed from those presented in the new filter (C, O, Na, Mg, Al, Si, K, Ca, and Ba). These results are according to Artaxo et al. (1998) and Godoi et al. (2004) who associated the Al, Si, Ti, Fe, and Ca to soil aerosol particles, P, S, and Cl to biomass burning, and Cr, Cu, Mn, Ni, Pb, V, and Zn to the structure of the plant cell wall.

Conclusion

Ultrafine particles showed high PM concentrations from biomass burning, where the diameter range that was responsible for the highest PM concentrations was 0.0–0.4 µm (backup stage). The predominant ions in the PM collected using the new portable isokinetic sampler were potassium (K⁺), chloride (Cl⁻) and nitrate (NO₃⁻), with potassium and chloride standing out as important ions in the characterization of biomass burning. The vast majority of these ions were present in PM smaller than 1.0 µm (B3). The Venturi scrubber developed optimum fractional and overall collection efficiencies. For the Andersen cascade impactor, the highest efficiencies occurred for the diameter ranges of 4.7–3.3 µm (S4) and 3.3–2.1 µm (S5) with maximum efficiencies of 94.3% and 90.6%. For the new portable isokinetic sampler, the highest partial collection efficiencies were obtained for \( V_{th} = 262 \text{ m/s} \) and had values of 99.6% for PM greater than 2.5 µm (B1); 98.9% for PM between 1.0 and 2.5 µm (B2); and 75.2% for PM less than 1.0 µm (B3). It was observed that the efficiencies, both fractional and overall, increased with the gas velocity at the Venturi throat. Thus, the best operating condition for the Venturi scrubber was \( V_{th} = 262 \text{ m/s} \) with a water flow rate of 2.5 L/min. The performance of the Venturi scrubber was very satisfactory, especially as it was responsible for collecting 75.2% of PM1.0 (B3), which is the most dangerous to the respiratory and cardiovascular systems. This shows that a compact, cheap, and practical piece of equipment for flare gas treatment, such as the Venturi scrubber and the cost-effective and efficient portable samplers, can be very interesting for industries that emit high concentrations of pollutants.

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**Data availability** The authors declare that all data supporting the findings of this study are available within the article and its supplementary information files.

**Declarations**

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