

Review

An Overview of Particulate Matter Measurement Instruments

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Abstract: This review article presents an overview of instruments available on the market for measurement of particulate matter. The main instruments and methods of measuring concentration (gravimetric, optical, and microbalance) and size distribution Scanning Mobility Particle Sizer (SMPS), Electrical Low Pressure Impactor (ELPI), and others were described and compared. The aim of this work was to help researchers choose the most suitable equipment to measure particulate matter. When choosing a measuring instrument, a researcher must clearly define the purpose of the study and determine whether it meets the main specifications of the equipment. ELPI and SMPS are the suitable devices for measuring fine particles; the ELPI works in real time. In health-related studies, a Diffusion Charger is the instrument that best characterizes the surface of ultrafine particles. Several methods and different particle measuring instruments should be used to confirm the values obtained during sampling.

Keywords: particle matter emissions; sampling; pollution; measurement instruments

1. Introduction

Maintaining ambient air quality at appropriate levels is one of the greatest challenges facing society today. There are many sources that discharge large amounts of polluting compounds into the atmosphere. Most of the sources are anthropogenic. Other than gaseous compounds, one of the most important pollutants produced by human activities is particulate matter (PM) (Demirbas [1] and Williams *et al.* [2]).

Particulate matter can cause serious problems in the environment. Some of the problems are the change in the radiation balance of the Earth, change in cloud formation, contribution to global warming, and reduced visibility, as reported by Tiwari *et al.* [3], Pipal and Satsangi [4], Gong *et al.* [5] and Li *et al.* [6].

Human health can also be affected by PM emissions. Ultrafine particles, for example, penetrate the pulmonary alveolus causing breathing problems. It can also induce oxidative stress, which can cause cardiovascular and neurological problems (Oberdörster *et al.* [7], Bai *et al.* [8] and Rafael *et al.* [9]). Studies have confirmed the relationship between mortality and exposure to PM (Peters *et al.* [10] and Brook *et al.* [11]). Considering the seriousness of human exposure to particulate matter, Franklin *et al.* [12] recommended that people in risk groups (those with cardiovascular disease, the elderly, diabetics, pregnant women, and those with lung disease) should limit the time spent outdoors on days when pollution levels are high.

People can be exposed to particulate matter in indoor or outdoor environments. Utell and Frampton [13] cited that particulate levels can vary from 5000 to 10,000 particles/cm³ in outdoor air. This number can increase to 300,000 particles/cm³ or even 1,000,000 particles/cm³ on streets with high traffic volumes. In studies conducted by Li *et al.* [6], particles with diameter less than 1 μm, which are the most harmful to health, were the ones that most contributed to air pollution caused by particulate matter in urban areas.

Today, a wide range of studies involving the measurement of particle have been published (Tissari *et al.* [14], Kwasny *et al.* [15], Hosseini *et al.* [16], Costa *et al.* [17], França *et al.* [18] Nakata *et al.* [19] and Leskinen *et al.* [20]). However, measurements of particles can vary widely, even those made for the same material and in the same place. This variation is mainly caused by the equipment used for measuring particles and the sampling procedures.

According to Nussbaumer *et al.* [21], there are many types of equipment available for measuring particulate material, which makes the choice difficult. Furthermore, particulate matter can range in size from nanometers to micrometers, which makes the choice of equipment even more challenging, as reported by Obaidullah *et al.* [22].

There are many challenges related to measuring particles, but they still need to be quantified in order to control emissions, which contribute to improving the quality of indoor and outdoor air.

Thus, the objective of this review is to help researchers choose the most suitable equipment for measuring particulate matter. An overview of the main methods and equipment for measuring the concentration and size of particles was presented. The characteristics, advantages, and disadvantages of measuring instruments were compared.

2. Review Articles about Measuring Particulate Matter

Review articles focusing on measuring particulate matter include the work of Nussbaumer *et al.* [21], Obaidullah *et al.* [22], Wilson *et al.* [23] and Giechaskiel *et al.* [24].

In the review proposed by Obaidullah *et al.* [22] the results regarding particle emission were presented in terms of mass concentrations, number concentrations and particle size distribution. The authors also described the measurement instruments employed to quantify particles. Their results were discussed only for small scale burners.

Wilson et al. [23] presented discussions about collection and outdoor particle measurement.

Techniques for particle measurement in small scale burners were discussed by Nussbaumer *et al.* [21]. The authors also presented results on particulate emission factors.

Giechaskiel *et al.* [24] analyzed the main equipment and techniques for measuring particles from vehicular combustion.

3. Instruments for Measuring Particulate Matter

There are several instruments for measuring different characteristics of particulate matter. The most important measurements of particles are particle concentration and particle size.

A particle size analyzer can determine the behavior of the particle in ambient air. Submicron particles can remain in the atmosphere for a longer period of time than those of larger size.

Particle concentration measurements are important to standardize emission limits, which guarantee the standards of air quality.

Particle are measured based on their classification. According to Obaidullah *et al.* [22], Wilson *et al.* [23], Wark *et al.* [25], and Vincent [26], the particles generated during the combustion process are classified as primary particles. Primary particles are directly emitted into the atmosphere. Primary particles are composed of fine particles, with diameter less than 2.5 μ m (PM_{2.5}), and by ultrafine particles, with diameters smaller than 0.1 μ m (PM_{0.1}) [23,26].

Particles generated by mechanical or chemical reactions in the atmosphere are classified as secondary particles. Secondary particles are coarse. They have diameters greater than 2.5 μ m. Coarse particles include particulate matter smaller than 10 μ m in diameter (PM₁₀) and total Suspended Particle Matter (TSP), as stated by Turner [27]. According to Wilson *et al.* [23], a secondary particle can contain particles from many sources; this occurs because they can be formed by the accumulation of several other particles.

Instruments that measure particle size distribution use the behavior of particles (diffusion, aerodynamics, and optical and electrical mobility), as described by Kulkarni *et al.* [28].

In this review study, special attention will be given to equipment used for measuring particle concentration and particle size. However, particle characterization involves study of particle morphology as well as chemical characterization.

In Figure 1, the most common particle measuring instruments were classified as concentration methods and size distribution methods.

3.1. Concentration Measurement Methods

In concentration methods, the PM concentration can be in mass (m), number (N) and surface area (S). These instruments are based in different measuring principles, and can be gravimetric, optical, microbalance, and electrical charge.

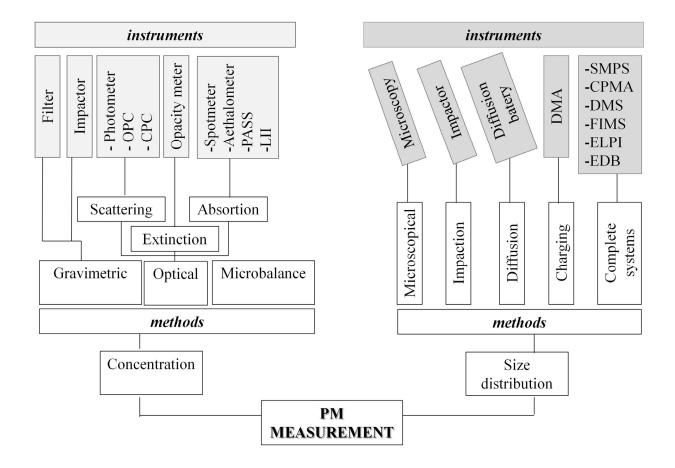


Figure 1. Methods and instruments for PM measurement.

3.1.1. Gravimetric Method

In the gravimetric method, the particle mass concentration is determined by weighing the filters before and after the sampling period.

Nussbaumer *et al.* [21] mentioned that the basic method to measure off-line PM mass concentrations, in combustion gases, is the gravimetric sampling in filters.

Giechaskiel *et al.* [24] described that the filter collects PM in all granulometric fractions (nucleation, accumulation, and coarse modes), unless there is a cyclone or impactor to remove larger particles. Nussbaumer *et al.* [21] cited the use of a set with pre-cyclones, which cut-off is of 10 μ m or 2.5 μ m, with an option to determine mass concentration.

Particle sampling, in filters, results in a resolution time of 15 min or more, therefore the identification of fast processes is not possible. However, particles collected in the filter can be analyzed chemically, as affirmed by Nussbaumer *et al.* [21].

Determination of PM mass can be altered, depending on the conditioning conditions of the filter. For this reason, Nussbaumer *et al.* [21] and Giechaskiel *et al.* [24] emphasized that the filters are typically packed under controlled conditions of temperature and relative humidity.

The gravimetric method is based on filters and Cascade Impactors. It can collect particles and evaluate their concentration. For more detailed analysis, other techniques are necessary, such as Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM).

Among the gravimetric instruments for measuring PM mass, Giechaskiel *et al.* [24] mentioned the Cascade Impactor. According to these authors such equipment are most used in the investigation of particle size distribution in mass. Cascade Impactors are frequently used as components of the systems that involve Size Distribution Methods. In this way, more information about these instruments were made available in Section 3.2.2.

3.1.2. Optical Methods

In the optical detection methods, aerosol particles are lit by a light beam and irradiate this light in all directions (scattering). Part of this light is simultaneously transformed in other energy forms (absorption), according to the description by Giechaskiel *et al.* [24]. As stated by these authors, extinction of the light can be calculated by the addition of scattering and absorption.

Optical instruments used for measuring particle concentration, in real time, can be based in the principles of scattering, absorption, and light extinction.

(a) Light scattering

Light scattering are classified as light dispersion by single particles, and scattering photometer by an ensemble of particles.

According to Giechaskiel *et al.* [24], the instruments of light scattering by an ensemble of particles include dispersion photometers which measure the intensity of scattered light in one or more angles. In a scattering photometer, the scattering light is measured by employing a photometer detector. Hinds [29] described that the light scattering photometers measure the scattered light from a combination of all the particles present in the optical detection volume. The authors emphasized that most commercial light scattering instruments use visible light (~600 nm) and measuring angles of 90°, 45°, or less than 30°. Among the scattering photometers, Vincent [26] mentioned the Respirable Aerosol Monitor (RAM). In the original version, the aerosol was aspirated with the help of a pump, and then passed through a cyclone that separated the respirable aerosol fraction. The aerosol entered the optical sensor zone, where the infrared light scattered in an angle of 45° to 90°, and the aerosol was detected by a photodiode. The author cited a new automated digital version of the instrument, the DataRam 4, which has the ability of data registry. This equipment presents concentration measurements and particle average size, besides other environmental information such as temperature and relative humidity.

Costa *et al.* [17], in their laboratory and field experiments, used a DataRam 4 to sample PM_{2.5}. According to them, this equipment is compact and performs sampling with data storage made continuously. DataRam 4 showed a good correlation with other instrument used to measure size and particle concentration. Chowdhury *et al.* [30] used a scattering photometer developed by University of California. This equipment is known as UCB-PATS (University of California Berkeley-Particle and Temperature Sensors). According to their description, the UCB-PATS use smoke detector technology, which combines chambers of photoelectric sensors (of light dispersion) and ionization (loss of ions by particles in suspension). This combination guarantees precise measurements of fine particles. The light dispersion chamber uses a light emitting diode (LED), with a wavelength of 880 nm, and a photodiode that measures the light intensity scattered in an angle of 45°. Even though the UCB does not select particles, using a device of traditional cut-off size as the cyclones, the photoelectric sensor is more

sensitive to particles smaller than 2.5 µm aerodynamic diameter and the ionization sensor is more sensitive to PM₁, as emphasized by the authors. Another scattering photometer is the DustTrak. This equipment was employed by Prado *et al.* [31] and Chowdhury *et al.* [30]. Chowdhury *et al.* [30] stated that this equipment is a portable light dispersion photometer by laser. In the DustTrak, the measurement of particle mass is obtained in real time. The aerosol is isolated in the optical chamber. In this way, the chamber is kept clean, which guarantees greater reliability in the measurements and low equipment maintenance.

With regards to the method of light scattering by single particles, Giechaskiel *et al.* [24] mentioned the Optical Particle Counter (OPC) as being the most used instrument. OPCs use a light source, normally a diode laser, to light a sample of particles in a given angle. A photodetector measures the light that scattered from the particles. Based on the intensity of the flash, particles can be counted and measured at the same time. For Giechaskiel *et al.* [24] OPCs are similar to Scattering Photometer. According to them, the main difference is that the OPC optical detection volume is smaller in relation to the Scattering Photometer, in such a way that only one particle is lit at once. The scattered light is detected by a photodetector as an electric pulse. The particle size is determined from the height of the electric pulse, using a calibration curve. The minimum limit for detection size is of particles with diameter above 100 nm.

An example of OPC is the SidePak Personal Aerosol Monitor model AM510 (TSI, Shoreview, MN, USA) used by Jiang and Bell [32] to evaluate PM_{2.5} concentration. According to these authors, the aerosol sample is aspirated to inside the collection chamber, in a continuous sequence. A laser lights one part of the aerosol flow. One 90° lens collects the light scattered by the particles and focus this light over a photodetector. The detection circuit converts the light in voltage, which is proportional to the aerosol concentration in mass.

The Condensation Particle Counters (CPCs) are also classified as light scattering counters. These counters are employed to measure the concentration of small particles. These particles do not scatter light sufficiently, in a way that conventional optical counters cannot detect this scattering. In the CPCs, small particles have their size increased by condensation of the produced vapor, from a working fluid, according to what is described by Giechaskiel *et al.* [24]. When the particles are enlarged by condensation, the CPC becomes similar to optical particle counters. In this manner, individual drops go through the focal point of a laser beam, with a flash of light. Each light flash is counted as one particle. The complexity of CPCs is in the technique to condensate vapor over the particles. When the vapor around the particles reach a certain degree of supersaturation, the vapor starts to condensate in the particles. The magnitude of supersaturation determines the minimum detectable particle of the CPC. During sampling of particles from burning wood chips, Leskinen *et al.* [20] and Torvela *et al.* [33] used a particle counter by condensation.

(b) Light absorption

Measuring instruments based in the principle of light absorption are used to measure the concentration of black carbon (BC), which composes the aerosol.

BC strongly absorbs light and is therefore a positive radiative agent, which contributes to climate changes and has been broadly investigated in atmospheric studies as described by Giechaskiel *et al.* [24]. Lack *et al.* [34] affirmed that light absorption by aerosols is one of the most uncertain parameters

associated with direct and indirect effects of aerosols in the climate. According to the authors, light absorption is one of the most difficult parameters to measure.

Among the employed techniques that are based on aerosol absorption measurement, Giechaskiel *et al.* [24] mentioned (i) the difference method, in which the absorption is obtained from the difference between extinction and scattering, (ii) the methods based in filters that measure light attenuation by the PM collected in a filter, (iii) the methods based on photoacoustic spectroscopy and (iv) the methods based on Laser Induced Incandescence (LII). The last two methods measure BC through particle heating. The heating is caused due to light absorption by the particles.

- (i) Spotmeters—These equipments are also known as reflectometers or smoke filter meters, due to the light absorption measuring principle based on light reflection over a filter. In a Spotmeter, the concentration of particles is obtained by filtering the exhaust gas in a paper filter, and recording of the ratio between the light reflected by this exposed spot and a non-exposed spot, as explained by Giechaskiel *et al.* [24].
- (ii) Aethalometer—As with Spotmeters, the Aethalometers are instruments used to determine BC concentrations. According to Giechaskiel *et al.* [24] and Krecl *et al.* [35], PM is collected in Aethalometers using a filter of quartz fiber. A change in light transmission (absorption) is measured in the filter, in several wavelengths. For Krecl *et al.* [35], the Aethalometer is one of the optical instruments based in filters, which is most used to determine the content of light absorbing carbon (LAC), besides the Particle Soot Absorption Photometer (PSAP). However, Giechaskiel *et al.* [24] pointed out that the conventional Aethalometers have a time resolution of several minutes, which is useful for environment monitoring, but slow for transitory emission tests. Versions with time resolution of 1 to 10 s became available more recently.

PSAP and Aethalometer measuring principle is the same, as stated by Krecl *et al.* [35]. According to the authors, these equipments are based on properties of light absorption by carbonated aerosols. They measure the attenuation of light transmitted through particles that are continuously collected in a filter. In the experiments by Krecl *et al.* [35], an Aethalometer series 8100 (Magee Scientific, Berkeley, CA, USA) was used to determine the concentration in mass of LAC in PM₁. The aerosol deposited in the filter were lit by a 880 nm LED and a 525 nm LED, for measures using the Aethalometer and the PSAP, respectively.

Gong *et al.* [5] used a seven-wavelength aethalometer to measurement of the mass concentration of BC and aerosol absorption coefficient.

- (iii) Photoacoustic Soot Sensor (PASS)—Light absorbing particles contained in the aerosol samples are periodically heated by absorption of amplitude-modulated light. According to Giechaskiel *et al.* [24], the heat conducted from the particles to the surrounding gas generates acoustic pressure waves that are registered by a microphone. The registered signal is proportional to the concentration in volume of light-absorbing particles <300 nm, and it is proportional to the surface of larger particles (>300 nm). Lack *et al.* [34] developed a very sensitive method to measure aerosol absorption in 532 nm, with an excellent response time, and they used photoacoustic absorption spectroscopy.
- (iv) Laser Induced Incandescence (LII)—According to Giechaskiel *et al.* [24], in LII, particles are heated right below the carbon sublimation temperature. Particle heating is done by a short laser pulse. After heating, particles reach incandescence and are decomposed. Particle decomposition is measured by a photomultiplier. According to Santoro and Shaddix [36] the incandescence intensity and

decomposition rate are analyzed to derive the number and average size of primary particles, and then the soot volume.

(c) Light extinction

In order to measure light extinction in aerosols, Mellon *et al.* [37] and Pettersson *et al.* [38] developed in laboratory a system for (i) Cavity Ring Down (CRD). Other equipment that measure light extinction is the (ii) Opacity Meter. These meters are broadly used to measure particles in diesel engines, as Öztürk [39] studies.

In the CRD experimental system developed by Pettersson *et al.* [38], aerosols were generated by atomization and drying. Dried particles were selected in size using a Differential Mobility Analyzer (DMA). Selected particles were counted in the CRD cell exit, with a counter for condensing particles (TSI, model 3022A).

Giechaskiel *et al.* [24] described that Opacity Meters measure the light fraction transmitted through an exhaust volume. Light extinction (opacity) occurs due to adsorption and scattering, in such a way that opacity is the difference between incident and transmitted light. As stated by the authors, measurements based on light extinction quantify particle concentration depends on path length and light wavelength, as well as the particle shape and its composition.

3.1.3. Microbalance Methods

Giechaskiel *et al.* [24] described that when the particles are collected, over the surface of an oscillatory microbalance element, those microbalances use the alteration of the resonance frequency to determine the PM.

There are two main measurement instruments that use the microbalance method: Tapered Element Oscillation Microbalance (TEOM) and Quartz Crystal Microbalance (QCM).

TEOM measures PM mass based on the alteration of resonance frequency of a tapered quartz wand, due to the accumulation of particles in a sampling filter, which is connected to the wand tip, as described by Giechaskiel *et al.* [24]. In combustion applications, there is a specific TEOM model in which the equipment is used along with a dilution system, as affirmed by Nussbaumer *et al.* [21]. As stated by Giechaskiel *et al.* [24], employment of TEOM in aerosol measurement, in vehicles, was not successful due to problems with humidity, pressure changes, and overload. However, Nussbaumer *et al.* [21] emphasized that TEOM is a well-established instrument when there is a need for measurements of PM₁₀ and PM_{2.5} in real time during biomass combustion. Jiang and Bell [32] used TEOM for continuous sampling of PM₁₀ in urban areas. This equipment was also employed by Elsasser *et al.* [40] for PM_{2.5} sampling.

In Quartz crystal microbalance, the quartz crystal has a piezoelectric property of changing its resonance frequency when there is a small addition of mass in its surface. As mentioned by Giechaskiel *et al.* [24] particles in QCMs are deposited by electrostatic precipitation in a fine quartz crystal resonator.

3.2. Size Distribution Measurement Methods

Size Distribution Methods measure the aerosol size, which can be represented by diameter (mobility, aerodynamic, among other equivalent diameters), and the aerosol concentration.

According to Giechaskiel *et al.* [24], particle size is measured based on properties such as geometric size, inertia, mobility, electrical mobility, and optical properties.

In general, measurement of particle size distribution is done from a combination of several measuring instruments. This combination involves loading of particles in corona charger, particle size classification (impactors or mobility classifiers), and detection (optical counters or electrometers).

3.2.1. Microscopy

According to Vincent [26], aerosol sampling for analysis of particle size, in a microscope, generally involves collection of particles directly from filters followed by filter preparation to improve visibility.

Besides the dimensions of solid particles, electronic microscopy also examines their morphology, as specified by Giechaskiel *et al.* [24].

Wentzel *et al.* [41] emphasized that image analysis offers a broad range of information such as rotation radius, size distribution of aggregates, fractal dimension, number of primary particles per aggregate, and size distribution of primary particles.

As stated by Giechaskiel *et al.* [24], one disadvantage of the microscopy method is the time spend to analyze a number of particles which is statistically enough.

3.2.2. Impactor

Impactors are instruments for measuring size distribution in mass, which working principle is gravimetry, with multiple impact stages; in some equipment multiple orifices are found.

According to Hinds [29], the most used impactors are the cascade type, which operate based on the inertial classification of particles.

As far as the working principle for the Cascade Impactors, Vincent [26] reported that the aerosol sample passes through a sequence of stages. In each stage, an air jet containing the aerosol reaches the impacting plate and particles larger than the cutoff diameter for the stage are collected. Smaller particles follow the gas flow that surrounds the collection plate and are collected in the next stage, in which the orifices are smaller and have conditions for greater air speed. This process continues until smaller particles are removed in the after-filter.

Nussbaumer *et al.* [21] mentioned some of the most used Low Pressure Cascade Impactors (Andersen Impactor, Dekati Low Pressure Impactor (DLPI), and Berner Low Pressure Impactor (BLPI)). The authors described that these impactors collect particles in the range of 30 nm to 10 μ m, and could extend the range of measurement to smaller particles, if using appropriate filters.

According to Giechaskiel *et al.* [24] and Vincent [26], the first impactor appeared in 1945, with cylinder nozzles (Casella Mk1) and the most recent version is the known Andersen Mk-II, with a multi-circular jet system.

Vincent [26] described that conventional Cascade Impactors operate at atmospheric pressure and do not select particles smaller than 0.4 µm. In this manner, the authors mentioned another family of Cascade

Impactors which are based on Micro-Orifice Uniform Deposit Impactor (MOUDI). MOUDI are precision Cascade Impactors that cover a broad range of particle sizes. They include a range of flow rate from 10 to 100 L/min and several combination of impacting stages. There are traditional models with eight stages and models with rotation of impacting plates. These last MOUDI models guarantee a more uniform deposit of particles over the plates, and also reduce bounce related problems as well as evaporation of semi-volatile material.

Venkataraman and Rao [42] described that MOUDI has 50% cut-point aerodynamic diameters of 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32, 0.18, 0.097, and 0.056 μ m on stages 1 to 10, respectively, and collects particles smaller than 0.056 μ m on a 37 mm quartz fiber after filter.

Another relatively recent impactor concept is the Electrical Low Pressure Impactor (ELPI). The ELPI operation principle is based on charging the aerosol electrically. This equipment is discussed in Section 3.2.8.

3.2.3. Diffusion Battery (EDB)

According to Vincent [26], particles with sizes below 0.1 µm are not strongly influenced by gravitational and inertia forces. Therefore, their behavior is not well represented by aerodynamic diameter, which is a common measurement in traditional equipment. Instead of this, particle movement is generally dominated by diffusion. In this way, the equivalent diameter in volume, obtained in a Diffusion Battery, becomes more appropriate for nanometric particles. According to Hinds [29], Diffusion Batteries were developed to determine the diffusion coefficients of the particles.

For Fierz *et al.* [43] recent gravimetric and optical methods are very insensitive to measure nanoparticles, and therefore are not appropriate for this task.

Giechaskiel *et al.* [24] described that Diffusion Battery separate particles by their mobility. According to these authors, these batteries are typically used as a switching valve to vary the effective length of the diffusion path, and with a CPC, to measure the concentration in number.

A new approach for Diffusion Batteries is the Electrical Diffusion Battery (EDB). In the EDB, particles are carried by a corona charger and then get into the Diffusion Battery that can be of two types: tube or screen.

According to Vincent [26], EDB collection efficiency is a function of geometric properties of the tube or screen, the flow rate, and particle size, expressed in terms of equivalent diameter in volume.

3.2.4. Mobility Analyzer

Among the Mobility analyzers, Giechaskiel *et al.* [24] mentioned the Electrical Aerosol Analyzer (EAA) as the oldest mobility analyzer, and the DMA as the most recent model.

Giechaskiel *et al.* [24] described that DMAs use bipolar diffusion charging to bestow a well-defined charge distribution in the aerosol. After loading, particles are inserted into an electrostatic classifier, allowing particle passage in a narrow range of electrical mobility. Classified particles are measured by an electrometer or CPC.

The Volatility Tandem Differential Mobility Analyzer (VTDMA) was found in the literature. According to Hossain *et al.* [44], the system is composed of two nano-DMA, two long-DMA (to cover a range of large size), a heating tube, and one Ultrafine Condensation Particle Counter (UCPC).

3.2.5. Centrifugal Measurement of Particle Mass

Centrifugal measurement of particle mass can be done by using a Centrifugal Particle Mass Analyzer (CPMA) or an Aerosol Particle Mass (APM).

According to Giechaskiel *et al.* [24], the CPMA is composed of two coaxial cylindrical electrodes, one internal and another external. The internal electrode turns a little faster than the external electrode. While passing by the electrodes, the loaded particles experience electrostatic and centrifugal forces, that act in opposed directions. Depending on the rotation speed and tension, between the electrodes, particles can penetrate the CPMA. Johnson *et al.* [45] described that the CPMA classifies an aerosol by the mass-to-charge ratio. According to these authors, the CPMA that measures mass-mobility is used upstream of a DMS (Differential Mobility Spectrometer), which measures the mobility size distribution of the mass-classified particles in real-time.

The main difference between the CPMA and APM is that in the APM both electrodes turn in the same angular speed, as affirmed by Giechaskiel *et al.* [24].

For Giechaskiel *et al.* [24], the advantage of these instruments is their ability to register particle mass without the need to collect particles for weighing.

3.2.6. Differential Mobility Spectrometers (DMS)

Among the spectrometers based on particle mobility, the most known are the Differential Mobility Spectrometers (DMS) and the Fast Mobility Particle Sizer (FMPS), mentioned by Hosseini *et al.* [16] and Hossain *et al.* [44].

However, other similar spectrometers also measure the particle mobility diameter: Scanning Mobility Particle Sizer (SMPS) and Twin Differential Mobility Particle Sizer (TDMPS).

These spectrometers are composed of a particle loader, a classification column and a series of detectors, as described by Giechaskiel *et al.* [24].

Giechaskiel *et al.* [24] emphasized that the SMPS is the most precise instrument for high resolution size distributions of aerosols from vehicle exhaust. Nussbaumer *et al.* [21] also mentioned the use of SMPS to measure concentration in number and size distribution of particles from biomass combustion. According to these authors, there are many versions of this instrument, working in a size range from few nanometers to 1 μ m.

As stated by Hosseini *et al.* [16], FMPS is made of two concentric cylinders (classification columns), a diffusion loader, and 32 electrometers, that cover the particle size range from five to 560 nm. The current containing positively charged particles flow along the sheath. High voltage between the two cylinders transports the particles from the point they are introduced to the other side that houses the electrometers. Next to the column top, the particles with greater electrical mobility are collected, and the particles with inferior electrical mobility are collected downstream.

FMPS uses an electrical mobility measurement technique similar to that used in SMPS. However, instead of a CPC, the FMPS spectrometer uses multiple, low-noise electrometers for particle detection. This produces particle-size-distribution measurements with one-second resolution, providing the ability to visualize particle events and changes in particle size distribution in real time.

Kamilli *et al.* [46] explained that TDMPS is composed of two DMAs, an Ultrafine Condensation Particle Counter (UCPC) and one CPC. Particles are charged and brought into charge equilibrium. With the help of two regenerative diffusion driers, inside the TDMPS, relative humidity conditions can be continuously monitored.

3.2.7. Fast Integrated Mobility Spectrometer (FIMS)

Giechaskiel *et al.* [24] stated that the Fast Integrated Mobility Spectrometer (FIMS) is composed by a charger, a size classifier, one condenser and one detector.

Kulkarni *et al.* [28] and Olfert *et al.* [47] described the FIMS working principle. According to these authors, the aerosol passes through a neutralizer, where the particles receive a charge distribution of bipolar equilibrium. In the sequence, the aerosol passes through a mobility analyzer, through which a gas flows (butanol-saturated). In the electrical field of the mobility analyzer, charged particles are separated in different paths, based on their electrical mobility. Classified particles are then transported by the flow in the field-free condenser, where supersaturation of butanol vapor condensates over the classified particles, increasing their size. At the condenser exit, one laser beam lights the drops, and the images are captured at 10 Hz with a camera. The images not only provide particle concentration but also the particle mobility diameter.

3.2.8. Electrical Low Pressure Impactor (ELPI)

As presented by Giechaskiel *et al.* [24], the ELPI classifies particles according to its aerodynamic diameter, besides measuring the concentration and particle distribution in number (7 nm to 10 μ m). Vincent [26] added that measurements using ELPI are close to real time.

Coudray *et al.* [48] considered that size distribution in number is easy and rapidly obtained using an ELPI, for biomass combustion. However, this technique is dependent on the aerosol density. For the authors, aerosol density from combustion sources is not well known and depends on several parameters. This can compromise the precision for size distribution in number, resulting from ELPI measurements.

Vincent [26] described that in ELPIs the particles are electrically charged as they are aspirated. According to Giechaskiel *et al.* [24], charging is done by an unipolar corona charger. Charged particles pass through a low pressure Cascade Impactor, which is composed by collection steps electrically isolated. Since the particles impact in one specific stage, they produce an electrical current that is registered in real time by an electrometer.

According to Giechaskiel *et al.* [24], an ELPI adaptation was developed to measure vehicle gases and it was named as Dekati Mass Monitor (DMM). One electrical mobility stage was added to this adaptation.

In the DMM, a combination of aerodynamic size data and mobility data is used to estimate particle density, thus allowing a conversion of the impactor data in real time mass concentration, according to what is described by Giechaskiel *et al.* [24].

3.2.9. Aerodynamic Sizers

Aerodynamic Particle Sizer (APS), Particle Size Distribution (PSD) and Aerosol Mass Spectrometer (AMS) are the equipment used to measure aerodynamic size.

In the studies conducted by Hossain *et al.* [44], a PSD was employed to measure PM aerodynamic diameter. However, a description regarding this instrument was not found, since its construction was restricted by the manufacturer.

APS is a spectrometer which working principle is based on the acceleration of aerosol sample flow through an accelerating orifice. The particle aerodynamic size determines its acceleration rate. Larger particles accelerate slowly due to larger inertia. At the nozzle exit the particles cross each other through two laser beams partially overlapped, in the detection area. The light is scattered when each particle passes through overlapped beams. One elliptical mirror, placed 90 degrees in relation to the laser beam axis, collects and concentrates the light over an avalanche photodetector (APD). Next, the APS converts light pulses in electrical pulses.

As discussed by Hosseini *et al.* [16], the APS is capable of measuring size distribution of particles in the size range of 0.5 to 20 µm. Sample particles are accelerated when the transporter gas flows through a converging nozzle. Due to inertia, particles cannot accelerate as fast as the gas, and there is a lack of speed in relation to the gas. Particle size is related to this lack of speed, which is measured in the exit of the nozzle through which the particles go through two closely spaced laser beams. Flight time between the two laser beams is then used to calculate the aerodynamic diameter.

The capacity to perform measurements for size distribution and aerosol mass, in one AMS, was compared to simultaneous measures using a DMA and a CPC, in the studies of Jayne *et al.* [49]. The AMS developed in the laboratory combines high performance aerosol sampling and an efficient system for particle detection, via thermal vaporization. According to these authors, the equipment is composed by three main sections: a chamber for aerosol sampling, a chamber for particle dimensioning, and a chamber for detection of particle composition.

4. Discussion

As described in this review, there are many different types of equipment for measuring particles commercially available. The characteristics of the main particles measuring equipment are described on Table 1. These characteristics can guide the researcher in choosing the most appropriate equipment for his needs.

The characteristics evaluated on Table 1 include: ability to sample particles in real time; need to dilute gas flow before collection; detection limit of the equipment; size range; accuracy of the equipment; and main advantages and disadvantages. In addition to the parameters evaluated in this work, there are other parameters that can be used for choosing the most appropriate PM meter, for example, durability, maintenance requirement, and the availability to measure the particle in humidified air stream or in the humidified environment.

Real-time particle sampling is a desirable characteristic in all studies because it allows processes such as combustion to be monitored. Furthermore, devices that enable particle collection in real time usually have an automated system for storing data. The Data Ram 4, which was used in the experiments of Costa *et al.* [17] and Amaral *et al.* [50], is an example of equipment that includes particle collection in real time and data storage.

Another characteristic that must be observed during the selection of the PM meter is whether a dilution system is needed. Dilution systems can reduce particle concentration and temperature of the

combustion gas. Thus, the use of a dilution system provides a more realistic and representative sampling of particulate matter emissions. Dilution reduced temperature, which extinguishes chemical reactions in the gas flow and prevents variation of particle size. Moreover, these systems provide greater durability for measuring instruments because of the requirements of entry of the analyzers. According to Nussbaumer *et al.* [21], most of the instruments available for particle measurement require dilution systems. Equipment such as Scattering, Spotmeter, Opacity, and DLPI do not require the use of a dilution system. For the TEOM device, the use the dilution system is optional.

Table 1. Comparison and specifications of different instruments for particle measurement. (Adapted from [21,22,24]).

| Instrument | Real Time | Dilution Required | Detection Limit | Size Range (nm) | A (%) | Advantages | Disadvantages |
|------------|--------------|-----------------------|-----------------------|-----------------------|----------|---|--|
| Filter | No | Yes | $10 \ \mu g/m^3$ | D | 5 | Simple; reliable; chemical analysis | Lots of work |
| Scattering | Yes | No (hot) | $10 \ \mu g/m^3$ | >50 | 30 | - | Measuring large PM |
| Spotmeter | No | No (hot) | $25 \ \mu g/m^3$ | All | 15 | Measuring BC | High response time |
| PASS; LII | Yes | Yes, No | $5 \mu g/m^3$ | >10 | 10 | Measuring BC | Necessitate calibration |
| Opacity | Yes | No (hot) | 0.1% opacity | >50 | 20 | - | Depends of several factors |
| TEOM | Yes | Depends sampling site | - | D | - | Agrees well with filter samples | If concentration is high, filter has to be changed |
| DLPI | No | No | - | 30–10,000 | - | Large size ranges | Not suitable for smaller particles |
| SMPS | No | Yes | 100/cm^3 | 3–700 | 15 | Very small particles | Not suitable for larger particles |
| FMPS | Yes | Yes | 1000/cm^3 | 5–700 | 25 | Fast; Indicates changes in process well | More inaccurate than SMPS |
| ELPI | Yes | Yes | $1000 / \text{cm}^3$ | 10–10,000 | 25 | Robust and large size range | Wide channels plates may affect the result |

Notes: A—Accuracy; D—Depends on pre-cutting.

When deciding which device is most appropriate, the researcher must evaluate issues related to the detection limit and size range of the instrument. The Spotmeter, which is used to measure concentration of BC through absorption of light, has been reported as being capable of measuring all the particle size ranges. Detection limit of this piece of equipment is $25 \mu g/m^3$.

Accuracy represents the closeness between the value measure by the instrument and the true value. It is a variable that should also be considered during the selection of PM meters. The device with highest accuracy on Table 1 was the Scattering Photometer (30%). On the other hand, the measurement methods based on filters were the least accurate (5%).

Methods using filters are not very accurate, but the main advantage of measuring particles using filters and conventional Cascade Impactors is the ability to perform a chemical analysis. However, this sampling method is very labor intensive. In this system, collection is not automatic and does not take

place in real time. This equipment is indicated for situations in which measurement includes coarse and fine particles and does not include ultrafine particles, as described by Wilson *et al.* [23].

Measurements related to UFP are important, particularly in health-related studies. In this case, the most recommended equipment is measures the numerical concentration of particles, as in the case of SMPS, FMPS, ELPI, and OPC.

Despite the low accuracy, the SMPS measures very small particles better than the FMPS. However, SMPS sampling is not in real time, as discussed by Nussbaumer *et al.* [21].

For the ELPI, which is a Cascade Impactor, the minimum limit of particle detection is 10 nm and the maximum is 10,000 nm. In addition, measurements are in real time and it is possible to conduct chemical analyses of the particles accumulated in Impactor dishes. With this piece of equipment, numerical concentration is determined online, and mass concentration offline.

In the study by Nussbaumer *et al.* [21] on particle emission from biomass burning, 17 institutes were interviewed about the equipment that they used to measure particulate matter. SMPS and ELPI were used by 50% of all institutes. FMPS was in use in one institute. Optical particle counters were used by 25% and opacity meters were not in use. APS was used by two institutes and TEOM was used by 40% of the respondents.

Despite the advantages of SMPS and ELPI in UFP measurement, these devices do not distinguish between UFP agglomerates and coarse particles. This distinction is extremely important in health-related issues. According to Oberdörster *et al.* [7], UFP agglomerates are more toxic than coarse particles. The health effects of UFP are related to their surface area. Thus, in research related to health, equipment must measure the surface area of the particle. In this context, Diffusion Chargers (DC) are the most suitable instruments.

The capacity of particles to acquire electrical charge favors the development of Diffusion Charger, as affirmed by Giechaskiel *et al.* [24]. According to these authors, sensors tend to show simple design, low cost, and high sensitivity.

In Diffusion Chargers, the aerosol is collected in the instrument and passes through an ionizer which carries the positive particles. The loaded aerosol goes through a trap to remove the excess of ions and through a DMA to separate loaded particles. The particles go to an electrometer, where the aerosol charge is measured, through recording of electrical current. Giechaskiel *et al.* [24] detailed the loading of particles by ions in the ionizer. The authors mentioned that the ions are normally derived from a corona discharge.

In addition to the characteristics discussed previously, when choosing equipment for measuring particles, the ability to transport the instrument to the sampling environment, that is, whether the equipment is portable, is an important factor to consider.

There is not a best instrument for measuring particulate matter, but a most appropriate instrument for each situation. In order to choose the best piece of equipment, the researcher must set the main goal of his measurement and learn the main characteristics of commercially available equipment.

Different methods of particle measurement are recommended to confirm the values obtained during sampling, as in studies of Hosseini *et al.* [16], Costa *et al.* [17], Hossain *et al.* [44], and Amaral *et al.* [50].

5. Conclusions

The aim of this work was to help researchers choose the most suitable equipment for PM measurement. In this context, the main conclusions were: to choose the appropriate instrument, the researcher must clearly define the purpose of the study, as well as understand the main specifications of the equipment; ELPI and SMPS are the suitable devices for measuring fine particles, and the ELPI works in real time; In health-related studies, a Diffusion Charger is the type of equipment that best characterizes the surface of ultrafine particles; The use of different methods and particle measuring equipment is recommended to confirm the values obtained during sampling.

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Author Contributions

Simone Simões Amaral was responsible for the bibliographic search and wrote the paper; Cleverson Pinheiro participed in the design of the study and analysis of the results; João Andrade de Carvalho Jr. and Maria Angélica Martins Costa were involved in the preparation, correction and approval the submitted manuscript.

Conflicts of Interest

The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

- 1. Demirbas, A. Combustion characteristics of different biomass fuels. *Prog. Energy Combust. Sci.* **2004**, *30*, 219–230.
- 2. Williams, A.; Jones, J.M.; Ma, L.; Pourkashanian, M. Pollutants from the combustion of solid biomass fuels. *Prog. Energy Combust. Sci.* **2012**, *38*, 113–137.
- 3. Tiwari, S.; Pandithurai, G.; Attri, S.D.; Srivastava, A.K.; Soni, V.K.; Bisht, D.S.; Anil Kumar, V.; Srivastava, M.K. Aerosol optical properties and their relationship with meteorological parameters during wintertime in Delhi, India. *Atmos. Res.* **2015**, *153*, 465–479.
- 4. Pipal, A.S.; Gursumeeran Satsangi, P. Study of carbonaceous species, morphology and sources of fine (PM2.5) and coarse (PM10) particles along with their climatic nature in India. *Atmos. Res.* **2015**, *154*, 103–115.
- 5. Gong, W.; Zhang, M.; Han, G.; Ma, X.; Zhu, Z. An Investigation of Aerosol Scattering and Absorption Properties in Wuhan, Central China. *Atmosphere* **2015**, *6*, 503–520.
- 6. Li, Y.; Chen, Q.; Zhao, H.; Wang, L.; Tao, R. Variations in PM10, PM2.5 and PM1.0 in an Urban Area of the Sichuan Basin and Their Relation to Meteorological Factors. *Atmosphere* **2015**, *6*, 150–163.

7. Oberdörster, G.; Oberdörster, E.; Oberdörster, J. Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles. *Environ. Health Perspect.* **2005**, *113*, 823–839.

- 8. Bai, Y.; Brugha, R.E.; Jacobs, L.; Grigg, J.; Nawrot, T.S.; Nemery, B. Carbon loading in airway macrophages as a biomarker for individual exposure to particulate matter air pollution—A critical review. *Environ. Int.* **2015**, *74C*, 32–41.
- 9. Rafael, S.; Tarelho, L.; Monteiro, A.; Sá, E.; Miranda, A.I.; Borrego, C.; Lopes, M. Impact of forest biomass residues to the energy supply chain on regional air quality. *Sci. Total Environ.* **2015**, doi:10.1016/j.scitotenv.2014.10.049.
- 10. Peters, A.; Dockery, D.W.; Muller, J.E.; Mittleman, M.A. Increased particulate air pollution and the triggering of myocardial infarction. *Circulation* **2001**, *103*, 2810–2815.
- 11. Brook, R.D.; Rajagopalan, S.; Pope, C.A.; Brook, J.R.; Bhatnagar, A.; Diez-Roux, A.V.; Holguin, F.; Hong, Y.; Luepker, R.V.; Mittleman, M. A.; *et al.* Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the american heart association. *Circulation* **2010**, *121*, 2331–2378.
- 12. Franklin, B.A.; Brook, R.; Pope, C.A., III. Air pollution and cardiovascular disease. *Curr. Probl. Cardiol.* **2015**, *40*, 207–238.
- 13. Utell, M.J.; Frampton, M.W. Acute health effects of ambient air pollution: the ultrafine particle hypothesis. *J. Aerosol Med.* **2000**, *13*, 355–359.
- 14. Tissari, J.; Lyyränen, J.; Hytönen, K.; Sippula, O.; Tapper, U.; Frey, A.; Saarnio, K.; Pennanen, A.S.; Hillamo, R.; Salonen, R.O.; *et al.* Fine particle and gaseous emissions from normal and smouldering wood combustion in a conventional masonry heater. *Atmos. Environ.* **2008**, *42*, 7862–7873.
- 15. Kwasny, F.; Madl, P.; Hofmann, W. Correlation of air quality data to ultrafine particles (UFP) concentration and size distribution in ambient air. *Atmosphere* **2010**, *1*, 3–14.
- 16. Hosseini, S.; Li, Q.; Cocker, D.; Weise, D.; Miller, A.; Shrivastava, M.; Miller, J.W.; Mahalingam, S.; Princevac, M.; Jung, H. Particle size distributions from laboratory-scale biomass fires using fast response instruments. *Atmos. Chem. Phys.* **2010**, *10*, 8065–8076.
- 17. Costa, M.A.M.; Carvalho, J.A.; Neto, T.G.S.; Anselmo, E.; Lima, B.A.; Kura, L.T.U.; Santos, J.C. Real-time sampling of particulate matter smaller than 2.5 μm from Amazon forest biomass combustion. *Atmos. Environ.* **2012**, *54*, 480–489.
- 18. França, D.D.A.; Longo, K.M.; Neto, T.G.S.; Santos, J.C.; Freitas, S.R.; Rudorff, B.F.T.; Cortez, E.V.; Anselmo, E.; Carvalho, J.A. Pre-Harvest Sugarcane Burning: Determination of Emission Factors through Laboratory Measurements. *Atmosphere* **2012**, *3*, 164–180.
- 19. Nakata, M.; Sano, I.; Mukai, S.; Holben, B. Spatial and Temporal Variations of Atmospheric Aerosol in Osaka. *Atmosphere* **2013**, *4*, 157–168.
- Leskinen, J.; Tissari, J.; Uski, O.; Virén, A.; Torvela, T.; Kaivosoja, T.; Lamberg, H.; Nuutinen, I.; Kettunen, T.; Joutsensaari, J.; *et al.* Fine particle emissions in three different combustion conditions of a wood chip-fired appliance—Particulate physico-chemical properties and induced cell death. *Atmos. Environ.* 2014, 86, 129–139.
- 21. Nussbaumer, T.; Czasch, C.; Klippel, N.; Johansson, L.; Tullin, C. Particulate emissions from biomass combustion in IEA countries. In Proceeding of the 16th European Biomass Conference and Exhibition, Zurich, Switzerland, 2–6 June 2008; p. 40.

22. Obaidullah, M.; Bram, S.; Verma, V.; de Ruyck, J. A review on particle emissions from small scale biomass combustion. *Int. J. Renew. Eergy Res.* **2012**, *2*, 147–159.

- 23. Wilson, W.E.; Chow, J.C.; Claiborn, C.; Fusheng, W.; Engelbrecht, J.; Watson, J.G. Monitoring of particulate matter outdoors. *Chemosphere* **2002**, *49*, 1009–1043.
- 24. Giechaskiel, B.; Maricq, M.; Ntziachristos, L.; Dardiotis, C.; Wang, X.; Axmann, H.; Bergmann, A.; Schindler, W. Review of motor vehicle particulate emissions sampling and measurement: From smoke and filter mass to particle number. *J. Aerosol Sci.* **2014**, *67*, 48–86.
- 25. Wark, K.; Warner, C.F.; Davis, W.T. *Air Pollution: Its Origin and Control*, 3rd ed.; Addison-Wesley-Longman: Boston, MA, USA, 1998.
- 26. Vincent, J.H. *Aerosol Sampling: Science, Standards, Instrumentation and Applications*; JohnWiley & Sons: Hoboken, NJ, USA, 2007.
- 27. Turner, J.; Colbeck, I. Physical and chemical properties of atmospheric aerosols. In *Environmental Chemistry of Aerosols*, 3rd ed.; Colbeck, I., Ed.; Blackwell Publishing Ltd.: Oxford, UK, 2008.
- 28. Kulkarni, P.; Baron, P.A.; Willeke, K. *Aerosol Measurement: Principles, Techniques, and Applications*, 3rd ed.; JohnWiley & Sons: Hoboken, NJ, USA, 2011.
- 29. Hinds, W.C. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, 2nd ed.; John Wiley & Sons: Hoboken, NJ, USA, 1999.
- 30. Chowdhury, Z.; Campanella, L.; Gray, C.; Al Masud, A.; Marter-Kenyon, J.; Pennise, D.; Charron, D.; Zuzhang, X. Measurement and modeling of indoor air pollution in rural households with multiple stove interventions in Yunnan, China. *Atmos. Environ.* **2013**, *67*, 161–169.
- 31. Prado, G.F.; Zanetta, D.M.T.; Arbex, M.A.; Braga, A.L.; Pereira, L.A.A.; de Marchi, M.R.R.; de Melo Loureiro, A.P.; Marcourakis, T.; Sugauara, L.E.; Gattás, G.J.F.; *et al.* Burnt sugarcane harvesting: particulate matter exposure and the effects on lung function, oxidative stress, and urinary 1-hydroxypyrene. *Sci. Total Environ.* **2012**, *437*, 200–208.
- 32. Jiang, R.; Bell, M.L. A Comparison of Particulate Matter from Biomass-Burning Rural and Non-Biomass-Burning Urban Households in Northeastern China. *Environ. Health Perspect.* **2008**, *116*, 907–914.
- 33. Torvela, T.; Tissari, J.; Sippula, O.; Kaivosoja, T.; Leskinen, J.; Virén, A.; Lähde, A.; Jokiniemi, J. Effect of wood combustion conditions on the morphology of freshly emitted fine particles. *Atmos. Environ.* **2014**, *87*, 65–76.
- 34. Lack, D.A.; Lovejoy, E.R.; Baynard, T.; Pettersson, A.; Ravishankara, A.R. Aerosol Absorption Measurement Using Photoacoustic Spectroscopy: Sensitivity, Calibration, and Uncertainty Developments. *Aerosol Sci. Technol.* **2006**, *40*, 697–708.
- 35. Krecl, P.; Ström, J.; Johansson, C. Carbon content of atmospheric aerosols in a residential area during the wood combustion season in Sweden. *Atmos. Environ.* **2007**, *41*, 6974–6985.
- 36. Santoro, R.; Shaddix, C. Laser-induced incandescence. In *Applied Combustion Diagnostics*; Kohse-Höinghaus, K., Jeffries, J., Eds.; Taylor and Francis: New York, NY, USA, 2002; pp. 252–286.
- 37. Mellon, D.; King, S.J.; Kim, J.; Reid, J.P.; Orr-Ewing, A.J. Measurements of extinction by aerosol particles in the near-infrared using continuous wave cavity ring-down spectroscopy. *J. Phys. Chem.* **2011**, *115*, 774–783.

38. Pettersson, A.; Lovejoy, E.R.; Brock, C.A.; Brown, S.S.; Ravishankara, A.R. Measurement of aerosol optical extinction at with pulsed cavity ring down spectroscopy. *J. Aerosol Sci.* **2004**, *35*, 995–1011.

- 39. Öztürk, E. Performance, emissions, combustion and injection characteristics of a diesel engine fuelled with canola oil–hazelnut soapstock biodiesel mixture. *Fuel Process. Technol.* **2015**, *129*, 183–191.
- 40. Elsasser, M.; Crippa, M.; Orasche, J.; Decarlo, P.F.; Oster, M.; Pitz, M.; Cyrys, J.; Gustafson, T.L.; Pettersson, J.B.C.; Zimmermann, R. Organic molecular markers and signature from wood combustion particles in winter ambient aerosols: Aerosol mass spectrometer (AMS) and high time-resolved GC-MS measurements in Augsburg, Germany. *Atmos. Chem. Phys.* **2012**, 6113–6128.
- 41. Wentzel, M.; Gorzawski, H.; Naumann, K.-H.; Saathoff, H.; Weinbruch, S. Transmission electron microscopical and aerosol dynamical characterization of soot aerosols. *J. Aerosol Sci.* **2003**, *34*, 1347–1370.
- 42. Venkataraman, C.; Rao, G.U.M. Emission Factors of Carbon Monoxide and Size-Resolved Aerosols from Biofuel Combustion. *Environ. Sci. Technol.* **2001**, *35*, 2100–2107.
- 43. Fierz, M.; Houle, C.; Steigmeier, P.; Burtscher, H. Design, Calibration, and Field Performance of a Miniature Diffusion Size Classifier. *Aerosol Sci. Technol.* **2011**, *45*, 1–10.
- 44. Hossain, A.M.M.; Park, S.; Kim, J.S.; Park, K. Volatility and mixing states of ultrafine particles from biomass burning. *J. Hazard. Mater.* **2012**, 189–197.
- 45. Johnson, T.J.; Symonds, J.P.R.; Olfert, J.S. Mass–Mobility Measurements Using a Centrifugal Particle Mass Analyzer and Differential Mobility Spectrometer. *Aerosol Sci. Technol.* **2013**, *47*, 1215–1225.
- 46. Kamilli, K.A.; Poulain, L.; Held, A.; Nowak, A.; Birmili, W.; Wiedensohler, A. Hygroscopic properties of the Paris urban aerosol in relation to its chemical composition. *Atmos. Chem. Phys.* **2014**, *14*, 737–749.
- 47. Olfert, J.S.; Kulkarni, P.; Wang, J. Measuring aerosol size distributions with the fast integrated mobility spectrometer. *J. Aerosol Sci.* **2008**, *39*, 940–956.
- 48. Coudray, N.; Dieterlen, A.; Roth, E.; Trouvé, G. Density measurement of fine aerosol fractions from wood combustion sources using ELPI distributions and image processing techniques. *Fuel* **2009**, *88*, 947–954.
- 49. Jayne, J.T.; Leard, D.C.; Zhang, X.; Davidovits, P.; Smith, K.A.; Kolb, C.E.; Worsnop, D.R. Development of an Aerosol Mass Spectrometer for Size and Composition Analysis of Submicron Particles. *Aerosol Sci. Technol.* **2000**, *33*, 49–70.
- 50. Amaral, S.S.; de Carvalho, J.A.; Costa, M.A.M.; Neto, T.G.S.; Dellani, R.; Leite, L.H.S. Comparative study for hardwood and softwood forest biomass: chemical characterization, combustion phases and gas and particulate matter emissions. *Bioresour. Technol.* **2014**, *164*, 55–63.
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