Methods for the analysis of airborne particulate matter

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Abstract: We provide a review of the common methodologies employed in the analysis of airborne particulate matter (PM). In this review, we focused on quantification of PM by different plant-based and instrument-based methods. First, we described sampling of PM by active and passive approaches. Then, different processing methods for PM samples required prior to final quantification are described. For final determination, the dust deposition, PM concentration in air in different fractions, and counting of PM in deposited form as well as in suspended form by various approaches are reviewed. We examined each method and their applicability in different environmental conditions. Finally, the described methods are evaluated with respect to their potential benefits and limitations in environmental monitoring and management.

Keywords: particulate matter; PM; direct and indirect sampling; deposition; quantification; particle counting.

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1 Introduction

PM stands for Particulate matter (also called particle pollution): the term for a mixture of solid particles and liquid droplets found in the air (the USA Environmental Protection Agency the USA EPA, April 2017). Some particles are quite visible which can be seen with the naked eyes such as dust, dirt, shoot, and some are very small which are seen by electron microscope. PM is further divided according to their aerodynamic size. If their size is < 10 µm, it is called PM_{10} or coarse particles, < 2.5 µm is called $PM_{2.5}$ or fine particles and < 0.25 µm is called $PM_{0.25}$ or ultra-fine particles. According to the size ranges, < 11 µm particles can enter the nasal passages of human respiratory system, 7–4.7 µm can enter the pharynx, 4.7–3.3 µm can enter the trachea. Particle with aerodynamic diameter 3.3–2.1 µm can enter the primary bronchi, 2.1–1.1 µm can enter the bronchi branches, 1.1–0.65 μm can enter the bronchiole and < 0.65 μm particles can enter the alveoli regions (Löndahl et al., 2006).

PM is one of the serious air pollutants because it can come in contact with humans through respiration and can cause several diseases. Long exposure of PM may cause lung dysfunction and cardiovascular diseases (Gilmour et al., 1996; Du et al., 2016). About 1 million people die every year due to lung dysfunction by particulate pollution as estimated (Shah et al., 2013; Chen et al., 2017). Those PM which are ≤ 2.5μm mainly come from anthropogenic sources and enters into human pulmonary alveoli, resulting in more serious health impacts (Hofman et al., 2013). It can also cause brain damage by entering in brain through olfactory nerves (Solomon et al., 2012). The international agency for research on cancer (IARC) and World Health Organisation (WHO) designate airborne particulates as group 1 carcinogen. It has been recognised by the WHO that the national mortality rate increased at the rate of 6%–13% per 10 mg/m^3 of $PM_{2.5}$ (Beelen et al., 2008; Pascal et al., 2014; Nikoonahad et al., 2017). Many studies have been done for PM exposure on human health and they suggest that it may cause several diseases like non-fatal heart attack, irregular heartbeats, decreased lung function, aggravated asthma and increased respiratory symptoms like irritation of airways, difficulty in breathing and coughing. (Correia et al., 2013; Cadelis et al., 2014).

PM is emitted in both direct and secondary form which has natural and anthropogenic sources (Zhang et al., 2015). PMs are deposited on earth surface by wet (snow, sleet and fog) and dry (dust, fly ash, soil dust) deposition. Some of the deposited or accumulated PM can again come back in the atmosphere by wind, and some remain attached to the plants. Plant leaves have special micro-morphological characteristics such as epicuticular wax, trichomes, stomata, leaf hairs, and roughness of surface. These features facilitate in the retention of PM at the leaf surface (Nafees et al., 2013; Liu et al., 2018). PM with size < 0.2 μm is permanently captured by the stomata and does not get removed by wind (Song et al., 2015; Ottelé et al., 2010; Viecco et al., 2018). Several studies are conducted regarding PM capturing by plants and it was found that trees and vegetation are effective for the trapping and absorbing particulates and many other pollutants, and it also act as a biological absorber or remover or filter of pollutants (Beckett et al., 1998; Lehndorff et al., 2006; Lu et al., 2008; Ogunrotimi et al., 2017).

Permissible limit of PM has been stated by many organisations like WHO, EPA and central pollution control board (CPCB). In most of the developing countries, the PM level is higher than the permissible limit because of increase in industrialisation and number of vehicles (Speak et al., 2012). Various instruments are installed for continuous measurement of all particulates. So, for controlling the pollution we need to have proper measurement of PM with respect to its concentration levels in various size ranges. To this end, very expensive methods and instrumentation are required for PM such as Photometer, Optical particle counter, Opacity metre, spot metre, air quality metre, air sampler, and PM counter. However, with the help of plants, one can easily monitor and plant strategies to remove the PM.

As per our knowledge, Palmer (1916) for the first time introduced an instrument for dust sampling (water-spray apparatus). This water-spray apparatus for sampling dust was adopted by the American public health association in 1917 (Greenburg and Bloomfield, 1932). Later on in 1932, impringer air dust sampling apparatus was used by the USA public health service which in introduced by Greenburg and Bloomfield (1932). Rowley (1940) invented instrument dust counter apparatus for measuring the number of dust particles in given volume of air. Penney et al. (1938) invented an electrostatic dust sampler for sampling dust including all type of PM which is present in atmosphere. This instrument get patented by United State Patent and trademark office in 1943. In 1945, a new instrument was described which sampled airborne PM and aerosols such as coarse dust, pollen and spores. The instrument shows greatest sampling efficiency in the range of 50–1.5μ (May, 1945). Initially, due to regulatory requirement and available technique, we use to study Total Suspended Particulate Matter (TSPM). However, with the gradual advancement of technique the size of PM in air is being monitored considering its significance with respect to their health impact. Now a days, we are able to study up to < 0.25 μm (ultra fine particles) which are suspended in air. So, knowledge of PM concentration in the air with their size measurement is a prerequisite for their management.

In this study, the recent developments on PM quantification in air are reviewed with a major focus on different strategy of the PM study along with its sampling methods, followed by its quantification methods and methods of PM counting. An emphasis has been given to plant based monitoring methods.

2 Sampling methods

In this section, the methods of sampling for PM collection are evaluated with respect to their feasibility in real environmental condition. Sampling methods are divided into two categories based on their capturing nature. One is the active method in which PM is collected by human-made equipment with some extra force applied for sampling. Second one is passive sampling method in which PM is naturally deposited (by Gravitational force) on plant surfaces itself. The application of various sampling techniques in quantification and counting of PM are summarised in Table 1.

2.1 Active sampling

Active sampling is done by either instruments or some man-made devices. In active sampling, atmospheric PM is forcefully collected (Suction force) by different instruments. PM can also generated or self-synthesised through active sampling methods.

2.1.1 Wind tunnel method

Wind tunnel is a type of instrument-based method for sampling of PM. Wind tunnel is the joint of two straight ducts with definite dimensions. Both are connected with the help of tunnel baffles (Figure 1). For instance, disco smoke machines (JEM hydrosonic 2000, UK) are used to generate NaCl particles instead of PM (Beckett et al., 2000a). Sampling leaves are placed in the tunnel and after sampling the NaCl concentration is measured by atomic absorption spectrometer (AAS) (Beckett et al., 2000b). Smith et al. (2003), used this method for identifying the PM deposition velocity of plant species.

Table 1 Quantification of PM and PM counting by different methods

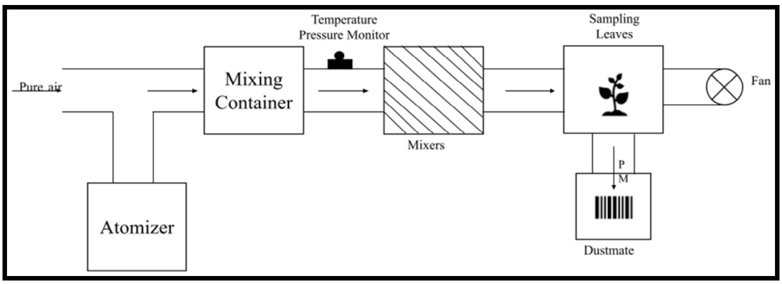
Category	*Sampling*	*Instrument used/ method*	*Quantification of PM/ dust (size range in µm)*	*PM counting (Size range in µm)*	*Location*	*Reference*
Plant based	Naturally grown plants	TPEM		0.2 µm–70.4 µm	Como, Italy	Terzaghi et al. (2013)
		SEM/image J.		0.1 µm–14.3 µm	Beijing, China	Yan et al. (2016)
		SEM/image J.		0.2 µm–10 µm	Stevinweg, Netherlands	Ottelé et al. (2010)
		SEM/image J.		<1.0 µm–>10 µm	Beijing, China	Shi et al. (2017)
	Synthetic leaves	SEM/image J.		0.1 µm–10 µm	Staffordshire, UK	Weerakkody et al. (2018)
	Living walls	SEM/image J.		PM10–PM1	Staffordshire, UK	Weerakkody et al. (2019)
	Naturally grown plants	SEM/image J./Gravimetric (Milipore USA filter paper)	0.2 µm–100 µm	0.2 µm–0.8 µm		
				2.5 µm–5.0 µm	Beijing, China	Song et al. (2015)
		Gravimetric (Whatmann 91 and 42, Cellulose nitrate fibre	>10 µm–0.2 µm	-	Terni, Central Italy	Sgrigna et al. (2015)
		Gravimetric (Whatmann 91 and 42, PTFE	>10 µm–0.2 µm	-	Norway & Poland	Sæbo et al. (2012)
		Gravimetric filter paper 20 µm and Cellulose nitrate fiber 0.45 µm and Whatmann 0.02 µm	PM1, PM2, PM3.5, PM5, PM7.5, PM10, PM15	-	Brigton, England and East Sussex, UK	Freer-Smith et al. (2005)
		PALL Filtering Setup	0.4 µm–10 µm		Beijing, China	Thao et al. (2014)
	-	Pall filtering setup With vacuum pump and metal sieve (Haver and Boecker)	0.2 µm–100 µm		Warsaw, Poland	Dzierżanowski et al. (2011)
		Metal sieve with vacuum pump	100–22 µm 22–1.6 µm	-	Sydney, Australia	Leonard et al. (2016)
		Evaporation method	TSPM	-	Lucknow, India	Yunus et al. (1985)
	Green roofs and living walls	Vacuum filtration with whatmann filter paper grade 91 and 42 and cellulose filter	74–10 µm 10–2.5 µm 2.5–0.2 µm	-	Santiago, Chile	Viecoo et al. (2018)

Table 1 Quantification of PM and PM counting by different methods (continued)

Category	*Sampling*	*Instrument used/ method*	*Quantification of PM/ dust (size range in µm)*	*PM counting (Size range in µm)*	*Location*	*Reference*
Instrument based	-	High Volume Sampler	PM10 Concentration	-	Lancaster, UK	Mitchell et al. (2010)
	Two-stage streaker sampler	OPC 1.108	-	0.25–32 µm	Genova, Italy	Mazzei et al. (2007)
	-	Six channel particle counter model 9012-2 (Met one instruments)	-	Count in 6 ranges 0.3–0.5 µm 0.5–0.7 µm 0.7–1.0 µm 1.0–2.5 µm 2.5–1.0 µm >10 µm	Milan, Italy	Tittarelli et al. (2008)
	-	OPC A10	-	0.17–7.7 µm	Karlsruhe, Germany	Heim et al. (2008)
	-	OPC WELAS 2100	-	0.30–40 µm	Karlsruhe, Germany	Heim et al. (2008)
	-	OPC Grimm 1.109	-	0.25–32 µm	Karlsruhe, Germany and Vienna Austria	Heim et al. (2008) and Burkart et al. (2010)
	-	OPC 1.108	-	0.3–20 µm	Vienna, Austria	Burkart et al. (2010)
	-	OPC PAS–1.108	-	0.3 –20 µm	Iowa, USA	Sausan et al. (2016)
	-	OPC – N2	-	0.38–17 µm, PM_1, $PM_{2.5}$, PM_{10}	Iowa, USA and Birmingham, UK	Sausan et al. (2016) and Crilley et al. (2018)

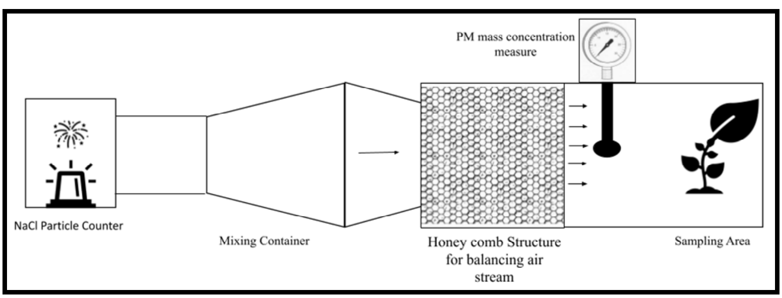
Another wind tunnel was developed by Räsänen et al. (2012). They changed the dimensions of the tubes. There is an aerosol generator (TSI 9603 Six-Jet Atomizer, TSI Inc. MN, the USA) for producing artificial fine PM by NaCl solution. After that a honey comb like structure comprised of 18 smaller tubes was placed which balances circulation of air streams. The sampling object is placed in the space which can also be a plant leaf or a whole plant (Figure 1). Räsänen et al. (2013) used this method for identifying the particle capturing efficiency and percentage of particle deposited on leaf surface.

Figure 1 Schematic diagram of wind tunnel experiment setup



Source: Zang et al. (2017)

Figure 2 Schematic diagram of wind tunnel experiment setup



Source: modified from Räsänen et al. (2012)

Zang et al. (2017) used a similar type of wind tunnel for find the PM removing capability of plant leaves. They added mixers for proper mixing of particles in air (Figure 2). Sampled leaves are inserted in this tunnel. In that tunnel, the pure air enters by atomiser and through mixing containers and mixer, and is sent to leaves. Temperature and pressure are monitored before despatch on leaves and secondary fan maintained the air at 20 m/s speed. After 6–10 minutes, the dust gets removed from the leaves and suspended in tunnel environment. Dust Mate (Turnkry, UK) is fixed inside the tunnel and, all PM is collected, which is suspended in tunnel air. DustMate environment monitor is handheld dust and fume detector. It measures TSPM, PM_{10}, $PM_{2.5}$, and PM_1. DustMate detect particles using turnkey's specially developed nephelometer. Nephelometer can detect every particles from the millions of particle per litre (Turnkeys instrument ltd.). The air concentration inside the tunnel is detected by the instrument DustMate (Turnkey, UK). The speed of the air is kept at 20m/s because >80% of the dust from leaves is removed at this speed (Zang et al., 2015).

2.1.2 Two stage streakier sampler

In this type, the PM is collected by the two-stage streaker sampler (Pixe International Corporation, the USA). Particles of size >10 µm are separated from the incoming air flux through pre-impact or in this instrument. In this way, only those particles are collected which are less than 10µm. After that, air passes through a thin Kapton foil (Pore size 2.5 µm) and particles of 10–2.5 µm are collected. Subsequently, the air passes through Nucleopore film (Pore size 0.4 µm) and particles of aerodynamic size in between 2.5–0.4 µm are collected. In this way, the sampling of the PM takes place in two stages (Prati et al., 1998). This method was used by Filippi et al. (1999) in hourly measurement of particulate concentration with streaker samplers and optical methods. They were able to monitor the aerosol mass concentration and elemental concentrations simultaneously in a continuous manner with the aid of Particle induced X-ray emission (PIXE). Mazzei et al. (2006) studied elemental composition and source apportionment of PM was done near a steel plant in Genoa (Italy) by two stage streaker samplers. Moreover, Mazzei et al. (2007) also studied a new methodological approach. The combined use of two stage streaker samplers and optical particle counters in Genova (Italy) for the characterisation of airborne particulate matter. They provide both the size and number of the particles in several size bins by this instrument.

2.1.3 PM generator

In this method, PM is generated in test room by a clean combustion (without fire) process (Viecco et al., 2018). By this method, the PM deposition on the plant leaf is measured. The PM is mixed well by placing fans in the test room so that the PM is distributed everywhere and settle down equally. Plants are placed inside test room for estimating the deposition of dust on the leaf surface. This method was used by Viecoo et al. (2018) for evaluating the ability of dry deposition of particulate matter on green roofs and vegetation of living walls to reduce urban atmospheric pollution in semi-arid climates

2.1.4 Aerosol generator

In this method, the sampling is done by generating aerosol by an instrument (QRJZFSQ-I) (Zhang et al., 2015a). This method is used in many studies. For instance, Zhang et al. (2015a) studied the adsorption capacities for airborne particulates of landscape plants in different polluted region in Beijing (China) and identified that middle leaves absorbs more airborne particulates as compare to broad leaves plants. Wang et al. (2015) studied PM absorption capacity of 10 evergreen species in Beijing by aerosol generator. They observed that there were differences in the PM retention capacities across leaf surfaces of selected plant species. Zhang et al. (2015b) studied absorption capacity of the air PM in urban landscape plant in different polluted region of Beijing through aerosol generator. They compared the ability of plant leaves to capture PM (TSPM and $PM_{2.5}$) in different polluted regions.

2.1.5 PM analyser

The PM analyser is a fully automated sampling instrument (Xact 625i) for PM_{10} and $PM_{2.5}$. In this instrument, a moving Teflon tape is used for sampling. This Teflon tape pore size will decide either do a sampling of PM_{10} or a sampling of $PM_{2.5}$. The sampling air is pulled through inlet pipe and passed through moving Teflon filter tape, where the particles are deposited and then moved to the analysis area, where X-Rays illuminate the sample, and the excited (in higher energy state) X-Ray fluorescence photons are collected by silicon drift detector (SDD) for metal analysis (Furgel et al. 2017). The collected spectra are then analysed and calibrated online (Furgel et al. 2020).

Ryder et al. (2020) used this technique to assess PM concentration and to identify their associated metals by Xact 625i, and to assess the contribution of both local and regional PM_{10} sources of the areas of Eden Park, California (the USA). Liao et al. (2020) studied trajectory-assisted source apportionment of winter-time aerosol using semi-continuous measurement. In this study Xact 625i was used to measure 32 elements form the air of commercial areas of Taipei city, Tiwan.

2.2 Passive sampling

Passive sampling is accomplished by natural process of deposition of PM at different surfaces and settling itself by the gravitational force.

2.2.1 Petri plate method

In this method, Petri plate and filter paper are used. Petri plates are covered with filter paper and holes are made in the middle of the Petri plate so that the rainwater can flow out (Pyatt and Haywood, 1989). For sampling of dust, the covered Petri plates are placed to the deposition areas. This method is very old and has some shortcomings which are, if it rains, the PM with size less than the filter paper's pore size will filter out along with the rainwater. Besides this, the methods is good for less plantation areas, open grounds and barren places, and is also cost effective.

2.2.2 Synthetic leaves method

To make synthetic leaves, the solution of sago (edible starch extracted from the pith or the spongy centre of the tropical palm tree *Metroxylon sagu*) is applied as a paint on leaf like shaped fabric. These synthetic leaves are attached to the plant and used for PM sampling as a direct source (Weerakkody et al., 2018). After sampling, the synthetic leaves are used for environmental scanning electron microscopy (ESEM) and the particle size is analysed.

Some drawbacks of this method are that the synthetic leaf surfaces are flat, so particles are not trapped properly and dust holding capacity decreases. Rain also causes damage to the synthetic leaves.

2.2.3 Through naturally-grown plants

In this method, the collection of PM is done from the plants which are grown naturally. Plant leaves are always exposed surface for PM deposition. So, PM can be collected naturally. Plant leaves have some morphological characters to capture the PM particles on their surface (Chen et al., 2017).

To this end, Freer – Smith et al. (1997) sampled and classified PM in different categories according to their shape and identifies their composition by Electron probe micro-analyser (EPMA). Weber et al. (2013) studied correlation between traffic density and amount of PM and, also classified plant leaves in 6 different categories according to their morphological character. Gajbhiye et al. (2016) used this method for dust sample collection. They studied air borne heavy metal accumulation with dust on the leaf surface in Bilaspur, Chhattisgarh (India) region. They were able to quantify the dust deposition and metals. They also quantified toxic heavy metals from sampled leaves and learned about hazardous air pollutants from the roadside environment. Chen et al. (2017) used this method for sampling PM from the 31 selected tree species from the study site at Beijing, China. They studied how leaf morphology interact with retention capacity by leaf dust weight measurement and find the best plant for retention PM2.5.

2.2.4 Plants grown in controlled environment.

In this method, the collection of PM is done by plants grown in controlled environment. For this purpose, one need to grow the plant in a clean place either in green house or a nursery. After growing the plant, sampling of PM is started by placing it where the sampling is required. Periodic sampling is also done by this method.

Beckett et al. (2000b) was able to find effective tree species for local air quality management by this method. They planted 5 tree species in 4 corners and 1 in the centre of a square area of with Dean Park, Brighton and East Sussex for sampling the PM from all directions. They found that plants with rough leaf surfaces are most effective for capturing PM. They also found that Mitchell et al. (2010) obtained magnetically clean tree by using this method. They grow plants under pollution free green-house condition. When tree grew up to 30 cm. and contained more than 40 leaves, it was placed at sampling site near Lancaster University UK for PM sampling. Popek et al. (2013) studied PM deposition on leaf surface of 13 woody plants at Pęchcin, Central Poland and phytostabilisation in leaf waxes. They grow all the plants on nursery and sampled. The sampling continued for 3 years.

2.2.5 Living wall method

In living wall system, those type of plants are used which are climbers or grow on wall for PM sampling. Walls are always exposed to air, and when we grow such plant on it, then it can be used for PM sampling.

To this end, Ottelé et al. (2010) quantified the deposition of PM on climber vegetation on living walls. Quantification of PM was done by SEM based image analysis by the software called Image j. In other study Werrakkody et al. (2019) designed a modular living wall system, a double-sided wall full of plants located facing a busy road for PM collection. They suggested that planting patterns and architecture of living walls and affect their ability to stabilise traffic-based PMs.

3 Sample preparation

As discussed above, in direct sampling methods (Perti plate, synthetic leaves, two stage streaker samplers, PM analyser) sampled dust does not require processing except if sampling was done through leaves (PM generator, Aerosol generator). In indirect methods, the PM is collected based on the natural deposition process. However, after deposition, the PM needs to be isolated/extracted from leaves by different methods.

3.1 By water

In this method, PM is removed from leaves with the help of water. Sampled leaves are washed with the help of deionised water by using brush (Lovett and Lindberg, 1992).

For instance, Freer-Smith et al. (1997) used this method for identifying the particle which accumulates on the Oak leaves in rough wood. Song et al. (2015) used this method for complete removal of leaf-deposited PM. They studied particle deposition rate per leaf square centimetre, and compared the five ever green species in Beijing, China. Chen et al. (2017) used this method for removing dust from the leaves and calculated the dust weight.

3.2 By water with chloroform

As PM can tightly adhere to the leaves of plant due to wax coating, there may be chance of incomplete removal with water due to less solubility. In this method, complete removal of dust is done from leaves by first washing with water and then followed by chloroform (Dzierżanowski et al., 2011).

Sæbo et al. (2012) used this method for examining PM accumulation pattern on 47 woody species which were commonly present in urban environment of Poland and Norway (Europe). Sgrigna et al. (2015) used this technique for separating PM (both leaf PM and Leaf wax PM) from leaves. They studied PM deposition on the leaves of Quercus ilex in an industrial city in central Italy.

3.3 By ultrasonic cleaning instrument

The ultrasonic cleaning instrument is also used for removal of PM from the leaves. For example, leaves were dipped in distilled water for 20 min, and this instrument was applied for separating the dust from leaves (Chen et al., 2003).

Chen et al. (2003) used this instrument for cleaning the leaves and studied dust absorption ability of conifers under heavily polluted and lower polluted status in Shenyang city, Northeast China. Liu et al. (2012) also used this instrument for removing the dust from leaves. They identified the dust retaining capability of afforested plant in Guangzhou, South China.

3.4 Evaporation method

This method has successfully been used for dust weight measurement from leaf surfaces. Sampled leaves are washed thoroughly with the help of brush and water, in a pre-weighed beaker is taken. The water is then completely evaporated in an oven or hot plate and final weight of beaker is taken. The resulting weight difference is the dust weight which was trapped in sampled leaves. (Yunus et al., 1985)

Yunus et al. (1985) studied dust holding capacity of some common plants near Lucknow city by using this evaporation method. Wang et al. (2007) used conical flask in the place of beaker at the time of evaporation. They identified physiochemical character of particle settled on leaf surface.

3.5 Vacuum filtration

Vacuum filtration is a technique for separating a solid product from a solution. The solution of solid particles in liquid form is poured through a filter paper in a Buchner funnel. The solid particles are trapped in a filter paper, and the liquid is passed through the funnel into the flask below, by a vacuum (Generalic Eni., 2018).

Viecco et al. (2018) quantified the dry deposition of PM by this method. They observed PM in three particle size fractions large, coarse and fine by using 10 µm, 2.5 µm and 0.2 µm pore size filter using Whatman filter paper grade 91 and grade 42 and ester cellulose filters (0.22 µm), respectively.

3.6 Metal sieve vacuum pumps

In this method, the metal sieve was used to eliminate bigger elements from suspension like PM. The PM is isolated on filter paper by filtering the PM suspended water by PALL filtering setup with a vacuum pump. (Thao et al., 2014). This filtering set has different fractions for capturing the PM in different categories according to their size. Particles are captured in different fraction using different filter papers.

Dzuerżanowski et al. (2011) used this instrument for quantitative analysis of PM deposition on foliage of 8 plant species which are planted in urban area of Poland in terms of particle size fraction and particle accumulated on leaf. They used 47 mm glass filter funnel with stoper assembly which is connected to the vacuum pump (KNF Neuberger, Inc, the USA). Thao et al. (2014) used this method for quantitative analysis of PM on the leaf surface and waxes. They separated particles in 3 fractions (10 µm, 3µm and 0.4 µm).

4 Analysis/quantification of PM

In order to know the actual pollution load is terms of PM concentrations, there are two methods: one is to estimate the PM/dust deposition rate and in another method, the actual mixing ratio/concentration is measured in different size fractions.

4.1 Quantification in terms of deposition rate

This is one of the easiest and cost-effective method for dust weight measurement. In this method, the first thing is to dissolve the PM into the water. This is based on the gravimetric method (weight-based measurement). We often consider the surface area of the object (such as leaf) for estimating the PM holding capacity per unit area. For instance, Shukla et al. (2008) studied the dust holding capacity of 5 plant species in the area of cement plant industry of Rewa, Madhyapradesh. They observed Azadirachta indica and Eucalyptus globulus have maximum deposition per cm2. Popek et al. (2013) studied the dust deposition rate per unit area of 13 woody plants species in the urban area of Poland. Irwe et al. (2017) measured the dust fall on the leaves of 15 plant species at Amravati, Maharastra. They observed dust holding capacity, pH of dust and total chlorophyll content of selected plant species. They found the highest dust holding capacity of Ficus benghalensis and Pongamia pinnata, respectively. We can also get dust weight in different size fraction by using different pore size filter papers.

For instance, Beckett et al. (2000b) used gravimetric methods to determine the quantity to PM_{10} captured by various broad leave trees at five polluted urban sites Brighton. Dzierżanowski et al. (2011) used this method for determining the quantity of PM deposition on the foliage of eight plant species commonly cultivated in urban areas of Poland. Liu et al. (2012) studied the dust retention capability of plants in urban environment of Guangzhou South China by using gravimetric method. Popek et al. (2013) used this method for the comparison of PM accumulation on the leaf surface and leaf wax of selected woody plants. Recommended for planting for mitigating the atmospheric PM in urban areas in Poland. They observed the PM in 3 different size fractions (10–100, 2.5–10, and 0.2–2.5 µm). During filtration, Whatman Type 91, Type 42 and PTFE membrane filters were used to capture particles < 10, 2.5, and 0.2 µm, respectively.

4.2 PM concentration in air

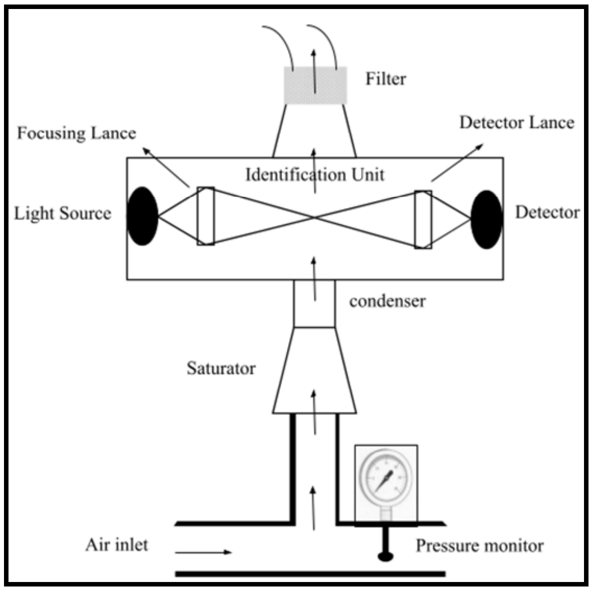
Estimating PM concentration in air is mainly done with a high-volume sampler. This is the recommended instrument for sampling a large air volume for suspended particulate matter (Jutze and Foster, 1967). This sampler consists of a vacuum motor attached to a filter holder. It was evaluated and described by Robson and Foster (1961). These air samplers typically sample more than 1,500 cubic metres (m^3) of air in 24 hours (Queensland Government, 2017). This instrument is used to collect the large known air volume through a pre-weighed filter for 24 hours. In this instrument, air capture by the air suction pumps and passed through pre-weighed filter paper. However, the PM is captured on pre-weighed filter paper, and airflow is monitored by flow sensors (Figure 3). Initially, a High-volume sampler is used for estimating the TSPM in air. After that, these high-volume samplers were also modified for estimating the reparable suspended particulate matter (RSPM).

Marrero et al. (2005) used a high-volume sampler to quantify metals and metalloids in the air of the urban environment of de Buenos Aires, Argentina. They also identified PM's source and their concentration in the air by continuous sampling. Leili et al. (2008) studied TSP and PM_{10} concentration in Tehran's central area (Iran). They also studied heavy metal associated with PM. They found that PM concentration in the air is higher than the national ambient air quality index (NAAQS) guideline.

In addition to the high-volume sampler, the new instrument with cascade impact or for sampling coarse aerosol was introduced by May in 1945. In cascade impact or, the PM is captured in different size fraction and their concentration in air can be measured. This instrument consists of 2–8 stages for the assessment of PM in different size ranges. Each stage consists of filter paper according to its pore size.

For instance, the airborne PM was sampled with a high-volume cascade impactor (Sira instrument Inc.) by Van Vaeck and Cauwenberghe (1978). They used a six-stage cascade impact or for volumetric analysis of TSPM at suburban residential of Wilrijk, Belgium. Chan et al. (2000) studied characterisation and source identification of PM_{10}. They also used a high-volume cascade impact or for aerosol sampling at Brisbane (Australia). They collected aerosol by 6 stage cascade impact or from 0.5 to 10 µm size ranges. Demokritou et al. (2004) used a multistage cascade impact or for the characterisation of atmospheric aerosol. They used a fully assembled compact impact or with eight impact or stages. This impact or measures PM size between 10 to 0.16 µm with backup filter paper for collecting the remaining PM. Pannanen et al. (2007) used a modified Harvard high-volume cascade impactor for mass measurement and chemical characterisation of size-segregated PM. Sampling was done in 6 European urban environments (Duisburg, Prague, Amsterdam, Helsinki, Barcelona and Athens). They studied PM mass concentration in six size ranges, including PM_{10} and $PM_{2.5}$.

Figure 3 Schematic diagram of condensation Particle counter, (CPC 3007)



Source: Modified from Matson et al. (2004)

5 Methods for PM counting

At present, PM quantification with their size ranges along with characteristics of different particles such as number, shape, size is in practice. This is due to increased concern and knowledge toward their link to human health and source apportionment. The various technique used for this are discussed below.

5.1 Condensation particle counter

Condensation particle counter is mainly used for ultra fine PM measurement. In these categories, one instrument, model CPC 3,007 measures particle size range from 0.01 to larger than 1µm. Another model P-TrakTM 8,525 measures 0.02 to larger than 1µm and the 3025 model done 3nm to 3µm range measurement. A competitive study of all three instruments was done by Matson et al. (2004). This instruments' particle detection principle is single particle counting and light scattering technology (Matson et al., 2004). The arrangement of the instrument, as shown in Figure 4.

Matson (2005) used both instruments for measuring the indoor and outdoor concentration of ultra fine PM in some rural and urban areas. Stapleton and

Ruiz-Rudolph, (2018) used P-TrakTM 8,525 model for measuring the PM concentration in indoor condition. They identified that the indoor plant could reduce the PM concentration in the air.

Figure 4 Schematic diagram of a High-Volume sampler

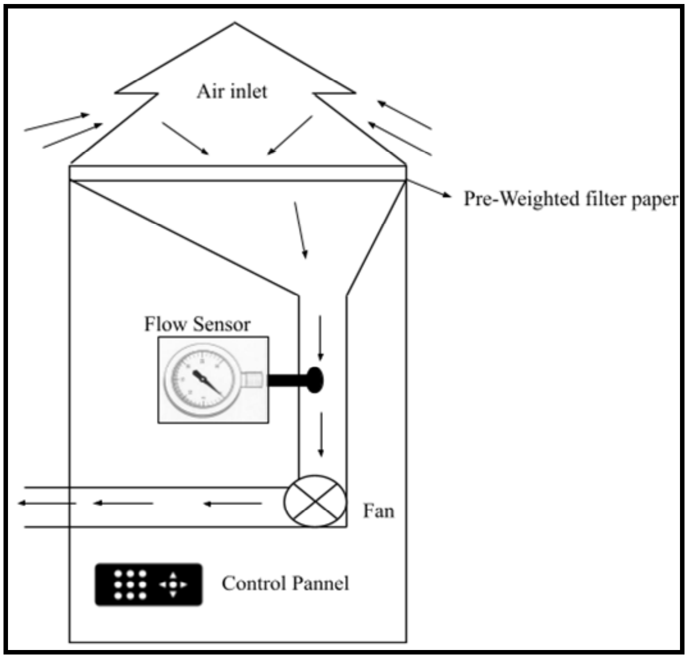
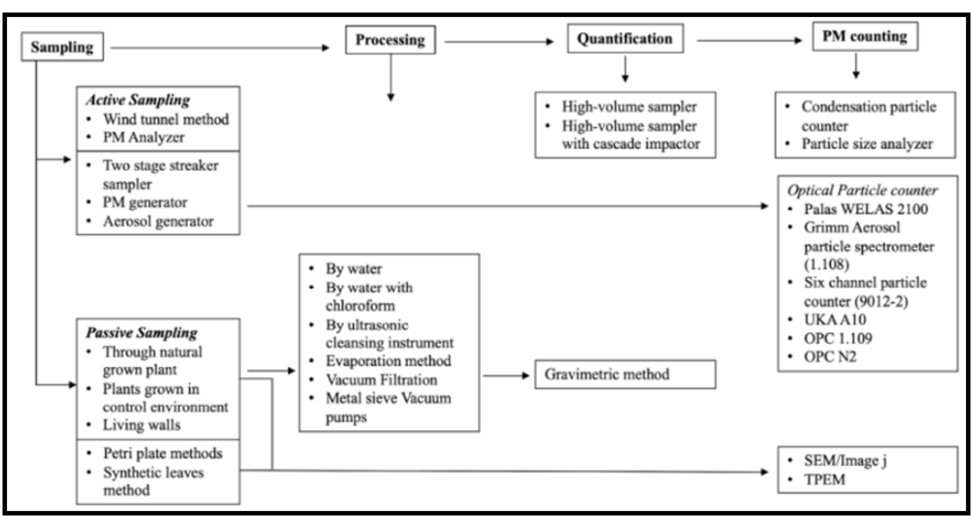


Figure 5 Overview of different PM sampling, quantification, and counting methods



5.2 Particle size analyser

The particle size analyser is performed particulate measuring using 90° laser light scattering technology, whereby semiconductor laser used as a light source. This technology enables this instrument to make very precise cut points for all three (PM_{10}, $PM_{2.5}$, $PM_{0.25}$) PM size classification. Particle size analyser (GRIMM model 107) is very small and portable. It was designed for PM_{10}, $PM_{2.5}$, and PM_1 environmental ambient air analysis. However, to the best of our knowledge, model 107 is the only PM monitor to offer dual technology consisting of both optical and gravimetric analysis (Grimm, 2002).

Lonati and Giugliano (2006) used this instrument for the size distribution of atmospheric PM at traffic sites in the Milan's urban areas (Italy). They also studied the role of traffic emission on PM concentration.

5.3 Scanning electron microscope/image J (SEM/image J)

It is an image-based technique. In this method, for the PM counting, sampled surface like a leaf, paper and another exposed surface, and photographs were taken with the electron microscope. The micrograph is taken with different magnifications (e.g., 100x, 250x and 500x). After collecting micrographs, the counting of particulate was done automatically with the software package called Image J. (Ottelé et al., 2010). Further information about the program can be found on http://rsweb.nih.gov/ij/.

Ottelé et al. (2010) quantified the amount of particulate matter deposition on climber vegetation on living walls and count the number of particulate matters on the leaves by Image J. and compare the PM deposition on the upper side and under side of the leaves. Sternberg et al. (2010) studied dust particulate absorption by ivy (Hedra helix) on the historical wall in the urban environment of oxford UK. Dust particles distribution on leaves were examined and analysed through SEM/Image J. SEM micrographs at different magnification for PM counting, 100x, 250x, 500x are used for PM_{10} $PM_{2.5}$ $PM_{0.2}$ respectively. Weerakkody et al., (2018) used this approach to quantify particulate matter densities on natural and artificial leaves. Weerakkody et al. (2019) used this method to quantify of PM level (PM_{10}, $PM_{2.5}$, PM_1) on the leaves. Gajbhiye et al. (2019) used this technique for PM size measurement and their distribution pattern. They were able to count the PM in between $PM_{0.2}$ to PM_{100} size ranges at both the surface of plant leaves.

5.4 Two photon excitation microscope (TPEM)

This method is used for the visualisation of particles presented on leaf surfaces. Leaf surface particles were excited using TPEM at 690 nm. The particle was detected between 300-500 nm with a minimum size of 0.2 μm up to 70.6 μm. Image was collected using Bio-Rad laser sharp 2000 imaging software and processed using confocal assistant 4.02 and Amira 5.0 (Terzaghi et al., 2013). After getting 3D images by TPEM, we assume that all particles are round in shape and particle size was determined by counting each particle's number of pixels.

Terzaghi et al. (2013) used this method for counting the particulate matter and their size distribution on leaf surfaces. 0.2 μm size particle was the smallest particle identified by using this method.

5.5 Optical particle counter

Optical particle counter (OPC) has a light scattering technique for counting the particulate matter in the air. OPC helps observe both the size and number of particulate matters in different size ranges quickly. (Mazzei et al., 2007). Particle measurements with optical equipment are based on the fact that some light is scattered when a particle passes through a beam of light. All such instruments rely on the detection of scattered light. Counting the pulses of scattered light that reach the detector can be used for measuring the particle number. On the other hand, optical scattering techniques can provide far more information than just a number. The size of the dispersed particle is related to the intensity of scattered light, and this relationship can be utilised to perform particle size measurements (Glantschnig and Chen, 1981).

5.5.1 Palas WELAS 2100

This instrument is similar to the A10 with a light source and a 90° scattering angle. Modle 2,100 has a patented T shape cross-section (Mölter and Munzinger, 1998; Mölter and Keßler, 2004a). In 2100 model, only one photomultiplier is used instead of two as in the A10 (Mölter and Keßler, 2004b).

Schwarz et al. (2018) studied PM_{10} and $PM_{2.5}$ concentration including particle size distribution and weight distribution of particulate matter by using WELAS 2,100 instrument. Tompkins et al. (2020) used this instrument for the detection of airborne particulates in a dental surgery room. Moreover, install WELAS 2100 instrument inside the room and observed some variation in the OPC background in the range of nominally 5–75 cm^{-3}.

5.5.2 Grimm aerosol laser particle spectrometer model 1.108

The OPC works on the principle of light scattering technique based on an advanced low water-sensitive laser source (λ = 675 nm). This instrument used dehumanisation system which operates when ambient relative humidity is higher than 70% (Mazzei et al., 2007).

Mazzei et al. (2007) used this method to characterise airborne particulate matter and size distribution of particulate matter and identified the sources of particulate matters.

5.5.3 Six channel particle counter (model 9012-2)

This instrument is manufactured by Met one instrument, Inc. Rowlett, Texas, the USA. Light scattering technology and a laser diode optical sensor measure particle size and numbers in 6 different size ranges (0.3→10 µm). Particle < 0.3 µm was not detected by this instrument. There sample speed is 2.83 L/min (Tittarelli et al., 2008).

Tittarelli et al. (2008) used six-channel particle counters for the examination of particle mass concentration and counting particle in different size (0.3→10µm) ranges in the environment.

5.5.4 UKA A10

UKA A10 was manufactured by and designed by Universität Karlsruhe. This instrument uses an intense white light source by Osram XBO-75 Xenon short-arc lamp to illuminate the particle suspended in air. In this instrument, two sensing photomultiplier branches are present in 90º opposite to each other. Due to its optical arrangement the instrument count particles in different size ranges (for more information Heim et al., 2008)

Heim et al. (2008) used these methods form for comparing the instrument with Palas WELAS 2100 and OPC 1.109.

5.5.5 OPC 1.109

OPC 1.109 instrument used 683 nm laser diode to illuminate aerosol beams, and a wide-angle collector optic to detect light pulses with a photodiode. For more information read Heim et al. (2008)

Shin et al. (2020) used this OPC 1.109 Grimm, (Germany) to measure the particles number concentration of PM_{10} and $PM_{2.5}$. Dinoi et al. (2017) used this instrument to classify the particles in 22 size intervals and measure the real-time concentration of $PM_{2.5}$.

5.5.6 OPC-N2

Alphasense Ltd manufactured this instrument in 2015. This is a low-cost optical particle counter that has recently become available for environmental studies. OPC-N2 (Alphanase, 2015) measures particle concentration in 16 different sizes from 0.38 to 17 µm and mass concentration (PM_1, $PM_{2.5}$, PM_{10}). This instrument contains a laser 25mW max that operates at a single power between 5 mW and 8 mW (Sousan et al., 2016).

Crilley et al. (2018) used this instrument to evaluate a low-cost optical particle counter for ambient air monitoring. This instrument was also used by Crilley et al. (2020) for air monitoring and measurement of $PM_{2.5}$ concentration.

6 Summary and concluding remarks

Given the potential health effects of airborne PM, an accurate assessment of their concentration in air in different environment conditions is very crucial. PM is found in different size ranges from larger to ultra fine particles from different sources. Concentration of PM varies in different areas. For this reason, it has often been a challenge to develop precise techniques for the assessment of PM.

With advancement of different methodologies, we can quantify airborne PM along with their associated toxic metals. For the sampling of PM, this paper describes the direct and indirect methods on the basis of their capturing nature. Direct method is instrument-based and indirect method is plant-based methods. PM settles on ground by gravitational force and plant leaf have special character for capturing PM. So, the plant-based sampling method is easier and cost effective as compared to instrument-based methods. After sampling we need to extract PM from plant leaves by different sample processing methods. Quantification of PM in plant leaves was initially done by gravimetric methods by estimating the deposition rate without considering the size ranges. Then, PM suspended in air was used to monitor by high-volume sampler mainly in TSPM and RSPM range. Later on, the samplers are improved to quantify PM in different size ranges by doing certain modifications in high-volume sampler and adding cascade impact or of different stages.

At present, in addition to the knowledge on PM concentration, the number of particles along with their shape and sizes are also of utmost importance. For this purpose, there are many methods introduced for PM counting. Some are fully automated instruments and some counting methods are plant dependent. The automated instruments basically work on light scattering technology. There is also a gradual advancement seen in OPCs. So, OPCs are used for real time PM concentration in air in different size fractions. SEM/Image j and TPEM are plant-based methods. These two methods used plant as sample and count the particles which are deposited on leaf surfaces.

For the final determination of these airborne PM, plant-based methods are very easy to perform. Plant based methods are based on naturally occurring phenomenon. In plant-based methods, we do not need to place any instrument on sampling areas. Moreover, plant-based methods are having implications in managing the PM in air in terms of their potential for removal of PM of different sizes from the atmosphere.

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