Particulate matter measurement indoors: a review of metrics, sensors, needs and applications

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Abstract

Many populations spend ~90% of their time indoors, with household particulate matter being linked to millions of premature deaths worldwide. Particulate matter is currently measured using particle mass, particle number and particle size distribution metrics, with other metrics, such as particle surface area, likely to be of increasing importance in the future. Particulate mass is measured using gravimetric methods, tapered element oscillating microbalances and beta attenuation instruments and is best suited to use in compliance monitoring, trend analysis and high spatial resolution measurements. Particle number concentration is measured by Condensation Particle Counters, Optical Particle Counters and Diffusion Chargers. Particle number measurements are best suited to source characterization, trend analysis and ultrafine particle investigations. Particle size distributions are measured by gravimetric impactors, Scanning Mobility Particle Sizers, Aerodynamic Particle Sizers and Fast Mobility Particle Sizers. Particle size distribution measurements are most useful in source characterization and particulate matter property investigations, but most measurement options remain expensive and intrusive. However, we are on the cusp of a revolution in indoor air quality monitoring and management. Low-cost sensors have potential to facilitate personalized information about indoor air quality (IAQ), allowing citizens to reduce exposures to PM indoors and to resolve potential dichotomies between promoting healthy IAQ and energy efficient buildings. Indeed, the low cost will put this simple technology in the hands of citizens who wish to monitor their own IAQ in the home or workplace, to inform lifestyle decisions. Low-cost sensor networks also look promising as the solution to measuring spatial distributions of PM indoors, however, there are important sensor/data quality, technological and ethical barriers to address with this technology. An improved understanding of epidemiology is essential to identify which metrics correlate most with health effects, allowing indoor specific PM standards to be developed and to inform the future of experimental applications.

1. Introduction

Poor indoor air quality (IAQ) has been estimated to be the 9th largest global burden of disease risk,[1] with the World Health Organization (WHO) attributing >4.3 million premature deaths to household air pollution in 2012, compared to 3.7 million deaths attributed to ambient (outdoor) air pollution.[2] The Institute for Health Metrics and Evaluation attributed 2.57 million premature deaths to household air pollution in 2016,[3] with Asia, Africa, Europe and the Americas contributing 74%, 23%, 1% and 2% respectively.[4] Particulate matter (PM), the sum of all solid and liquid particles suspended in the air, is a major metric of IAQ. PM is strongly associated with myocardial infarction, strokes, heart failure, asthma, chronic obstructive pulmonary disease and lung cancer.[5] PM <200nm in diameter has also been observed in the brain, and this may be causally linked to neurodegenerative diseases, for example, Alzheimer's disease.[6] It is well established that modern populations on average spend >90% of their time indoors, and on a daily basis indoor air contributes 19-76% of an individual's exposure to particles <100nm in aerodynamic diameter.[7,8] Brunekreef[9] has summarized the short and long term effects of PM on health.

Historically, the focus of measurement has been on outdoor PM. However, indoor PM is being increasingly identified as an area that requires more research. Understanding the sources, sinks and behavior of PM within indoor environments is important to accurately predict personal exposures and population health burdens, as well as to design practical and effective mitigation strategies.

Atmospheric PM is generally measured using two main metrics; particle mass concentration (Pmass) and particle number concentration (Pnum). Pmass is the mass of particles within a given volume (usually $\mu g/cm^3$) and Pnum is the number of particles within a given volume ($particles/cm^3$). However, there are other metrics that provide valuable information on the nature of atmospheric PM. Another important characteristic of PM is the particle size distribution (Psd); this is the particle concentration (either mass or number) measured over a range of different particle sizes. The chemical composition of particles can also be measured, although chemical composition is not covered in detail by this paper. It is still largely unknown how each of these metrics relate to health effects and therefore which metric is the best suited to measuring health risk.

The challenges associated with measuring PM in the indoor environment are distinctly different to those of measuring PM in the outdoor environment. Indoor environments can have much more variable PM levels than outdoors,[10] in absolute terms and over small distances. PM levels can be much lower than outdoors when there are no dominant indoor sources; however, in the presence of indoor sources, PM levels can rapidly rise to several orders of magnitude greater than outdoor levels. The confined nature of indoor environments allows PM to accumulate, but can also lower PM below ambient concentrations through removal of particles during building shell penetration. With pressure placed on developing energy efficient buildings with low heat losses and therefore low air exchange rates, accumulation of indoor generated PM pollution is likely to be an increasing problem.[11] This means that PM monitoring equipment used indoors needs to be able to accurately measure PM over a wide range of concentrations. Indoor particle events are frequently time and space specific; brief, intermittent and highly variable.[8] This means that high spatial and temporal resolution measurements are necessary to further understand the controls and influences on PM. High temporal resolution measurements are common practice, with any "real time" measurement instrument providing sufficient resolution in most cases; however, spatially varying measurements are less common with campaigns rarely deploying multiple sensors within a single indoor environment.

There are many other practical issues associated with measurement of indoor PM. There are constraints of size, noisiness and intrusiveness placed on equipment. For example, in an occupied school classroom it would be inappropriate to deploy large noisy equipment. This is much less of an issue with outdoor measurements. Some of the most severe indoor air pollution (IAP) is experienced in middle and low-income homes in both rural and urban areas of less economically developing countries (LEDCs), often with high levels of ambient pollution and use of coal or biomass stoves. Many of these locations lack access to electricity, and hence, measurements must be made with either battery-operated devices or passive samplers. The increasing focus on indoor PM has driven researchers to develop smaller, lighter, inexpensive battery-operated sensors. However, developing sensors that are sufficiently sensitive when measuring over a large range of concentrations and size ranges of PM is challenging.

A wide range of technologies and sensors has been developed to measure PM. These vary in precision, accuracy, sensitivity (detection limits), time resolution and cost. However, the appropriate ranges for these criteria can vary substantially when considering the size, cost and experimental applications. For example, when measuring in unoccupied spaces (as opposed to occupied spaces), what is reasonable in terms of size, weight and noisiness of equipment is very different. It is important to understand how these sensors vary, to correctly select the most effective for any given measurement scenario.

This paper critically reviews PM metrics, the sensors and measurement techniques associated with these metrics, and the sensors and techniques that are most appropriate for each experimental application. The future of IAQ and PM measurement, the challenges, solutions and anticipated shifts in focus are also discussed. This will aid future studies in selecting the most appropriate metrics, measurement techniques, and sensor technology, as well as highlighting the challenges associated with measuring PM indoors.

The PM sensors selected for review are based on the following criteria;

a. The sensor must operate within sensible ranges for the criteria listed above, whilst considering their applications.
b. There must be evidence that the sensor has been used to measure PM within indoor environments, with substantial benefits compared to other sensor types.

PM is currently measured using gravimetric, optical, oscillating microbalance, beta-attenuation and electrical current techniques. Some of the sensors can measure more than one of the metrics listed. Indoor measurements are usually collected in the center of the environment, at 0.75-1.8m height representing the breathing zone, with a height of 1.5m recommended.[12]

Current developments in PM monitoring are primarily influenced by PM sensors that have traditionally been used in occupational health and regulatory compliance monitoring, and developments in miniaturization & wireless technology. Low-cost, portable sensors, capable of measuring high temporal resolution concentrations have been at the forefront of meeting the rapid increase in public awareness and interest in quantifying personal exposure to IAP. It is important to consider how these sensors may play a role in measuring IAQ specifically.[13] Many of the sensors now being used in indoor environments were initially developed to measure vehicular emissions or industrial environments which tend to have high concentrations of pollutants compared to indoor environments.[14] Therefore, it is important to establish which role each sensor can most effectively play in IAQ measurement. Table 1 outlines the sensors reviewed in this paper and the abbreviations used where appropriate.

Measurement Method	Sensor	Abbreviation
Gravimetric	Gravimetric Filters	N/A
	Impactors	N/A
Optical	Photometers	N/A
	Optical Particle Counter	OPC
	Condensation Particle Counter	CPC
	Scanning Mobility Particle Sizer	SMPS
	Fast Mobility Particle Sizer	FMPS
	Aerodynamic Particle Sizer	APS
Electrical	Diffusion Size Classifier	DiSC
	Nanoparticle Surface Area Monitor	NSAM

Table 1. A list of reviewed sensors and their abbreviations categorized by their measurement method.

Oscillating microbalance, beta attenuation, and low-pressure impaction measurement methods are not included within this review; they are less commonly used indoors and more practical alternatives are often available. Detailed descriptions of these methods are outlined by this international standard.[15]

2. Review of Metrics

In the atmosphere there are three broad particle modes; the fine/nuclei mode (<0.1μm), the accumulation mode (0.1-2.5μm) and the coarse mode (>2.5μm); in short, these are the consequence of physical processes such as emission, nucleation, accumulation and scavenging. Pmass is usually measured as $PM_{2.5}$ or PM_{10} and this is the mass of all particles with an aerodynamic diameter of ≤2.5μm and ≤10μm, respectively. PM_1 is also increasingly used but is not yet widely implemented and there are discussions currently on whether $PM_{0.5}$ or $PM_{0.1}$ should be introduced in the future.[16] PM_{10} and PM_1 are arbitrarily selected as size cut-offs out of convenience, whereas $PM_{2.5}$ is selected more purposefully to include accumulation and fine particles (which remain suspended for longer), but to exclude the coarse particles, which are deposited more rapidly. These cut-offs are also indicative of historic progress; for example, the UK Department of Environment, Food and Rural Affairs (DEFRA) introduced PM_{10} and $PM_{2.5}$ in 1997 and 2007, respectively, as sensing technologies and understanding of PM improved. Other measurement ranges include total suspended particulate (TSP), a measurement of the mass of all particles present in the air, and inhalable, thoracic and respirable size fractions, used in health-related sampling. The inhalable, thoracic and respirable fractions represent particles that can enter the respiratory system through the mouth and nose (50% penetration efficiency (D_{50}) at 100µm), pass through the larynx and enter the bronchial region of the lungs (D_{50}=10µm) and enter the deepest part of the lungs, the ciliated alveoli (D_{50}=4µm), respectively.[17] It should be noted that these definitions were developed in a workplace exposure context. The EPA[18] provide a useful visualization of the sizes of $PM_{2.5}$ and PM_{10} and Nazaroff[19] outlines the sources, compositions and behaviors of different particle size fractions in indoor environments.

Particle Mass

Pmass is the most commonly used metric to measure PM; it is the easiest metric to measure and can be measured accurately at a relatively low cost. Due to the characterization as PM_{10}, $PM_{2.5}$ and PM_1, it is convenient to draw comparisons between different indoor environments and measurements collected by different equipment. Easy comparisons allow us to develop appropriate Pmass concentration standards. Currently there are no universal standards for Pmass specifically for indoor environments. The WHO recommends outdoor Pmass guidelines for $PM_{2.5}$ of 10µg/m^3 (annual mean) and 25µg/m^3 (24 hour mean) and for PM_{10} of 20µg/m^3 (annual mean) and 50µg/m^3 (24 hour mean).[20] However, these standards are not indicative of where adverse health effects begin to occur (for $PM_{2.5}$, this is currently understood to be just above background concentration at 3-5µg/m^3).[20] Rather, they are the lowest levels at which "total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to $PM_{2.5}$".[20] The WHO investigated whether it was necessary to introduce specific indoor Pmass standards.[21] They concluded that because there was no significant difference between the hazardous nature of PM in indoor and outdoor environments, and because indoor PM levels are often greater than those outdoors (in the presence of indoor sources) it was not necessary to introduce any specific, more stringent indoor Pmass standards. WHO outdoor Pmass guidelines are therefore assumed to apply to indoor environments.[21] This assumption makes sense for now, given our currently limited understanding of the nature of IAQ; however, in the future it is likely that specific indoor standards will be established, when the effect of composition and concentration on health are better understood. For example, if it is discovered that acute exposure to PM has more detrimental health outcomes than chronic exposure to PM, the standard might change from something based on the average to something that reflects the number of times a certain risk threshold is exceeded and the duration of that exceedance.

Particle Number

As measurement technologies have advanced and as focus moves towards the importance of ultrafine particles (UFPs, particles ≤100nm in aerodynamic diameter), Pnum is becoming an increasingly used metric for measuring PM within indoor environments. Although the Pnum metric is being used increasingly in outdoor and indoor PM studies, it was originally used to characterize vehicular exhaust emissions.[22] Unlike Pmass, Pnum varies by several orders of magnitude - from $<10^3$ particles/cm^3 in relatively clean environments to $>10^6$ particles/cm^3 when there are dominant sources of indoor pollution.[23] In contrast to Pmass, Pnum is mostly made up of smaller particles. For example, Pnum concentrations have been measured to be two orders of magnitude greater within the <0.5μm size range than in the 0.5-18μm size range.[24] This means that when fine or UFPs are the focus of a study the Pnum metric is often employed. Currently there are no standards for Pnum in indoor or outdoor environments,[25] likely due to the relatively recent adoption of ambient Pnum measurements, the highly variable nature of the Pnum metric, and the difficulty of comparing studies measuring Pnum. Epidemiologists have suggested that Pnum is a more important predictor of health impacts than Pmass.[26,27] This is because Pnum better represents the smaller particle size fractions, which penetrate further into the respiratory system, potentially causing more damage.[28]

Particle Size Distributions

Understanding the Psd in indoor environments is important for several reasons. The size of particles determines how far they can penetrate the respiratory tract. Smaller particles often have a higher toxicity per unit mass, due to a larger surface area to mass ratio.[29] The Psd metric is commonly used in studies which attempt to identify the major PM sources within indoor environments, and to understand the important removal processes and residence times of PM.

The Future of Ultrafine Particle Metrics

There is currently much debate on what should be the flagship metric for the measurement of UFPs. The metrics mainly considered are Pnum, surface area, "active" surface area, and particle reactivity (which relates to chemical composition). There is general agreement that the metric should provide insight into how PM interacts with the body through intake, uptake and transport. Therefore, there is some consensus that a surface area-related metric should be introduced, since these better correlate with the biological and toxicological activity of particles than either Pmass or Pnum.[30] However, there are concerns over whether it is plausible to achieve accurate measurements with relatively simple equipment. It seems likely that the UFP maximum size cut-off will be moved from 100nm to between 200-500nm and that diffusion chargers may be the most effective way of measuring the proposed "active" or "lung deposited surface area (LDSA)".[30] Measuring compliance or exposures using the Pmass and Pnum metrics can be of limited use, given that physiochemical properties of particles give rise to varying levels of toxicity and this toxicity is also an important determinant of health effects. Instead, identifying and quantifying the sources generating the most reactive species of UFPs is suggested.[30]

The Future of Epidemiological Metrics

There is strong agreement that future metrics should provide more information on the health impacts of particles than just physical properties. Particle length concentration and active or geometric surface concentrations might be more indicative of a particle's effect on health than Pmass or Pnum.[31] Whereas Pnum takes no account of particle size, particle length concentration is Pnum multiplied by the diameter of particles within a given size range. The geometric surface area concentration equals the particle number concentration multiplied by the particle's diameter squared, within a certain size range. Although the geometric and active surface areas both relate to particle diameter, the geometric surface area makes the assumption that particles are spherical whilst active surface concentration does not.[32] These may eventually become more important metrics for PM in epidemiological studies.

3. Characterization of Measurement Approaches and Sensors

Here, principles of measurement techniques and sensors associated with each PM metric are briefly outlined, and references to more detailed descriptions are provided.

Particle Mass

Pmass is measured using gravimetric and optical methods.

Gravimetric methods are based on weighing a filter sample before and after a sampling period and calculating Pmass from the difference in weight. Filters have a collection substrate on which particles of all sizes are deposited, unless there is a cyclone or impactor used to remove larger particles. Conventionally this is active sampling, with a pump pulling air through the filter at a known flow rate, however, passive samplers that do not require a pump have also been developed.[33] Passive samplers are much lighter, smaller and less noisy than pump-operated active samplers, but must be deployed for longer times to be effective and – depending on the design - can be influenced substantially by wind speed and particle size. The University of North Carolina (UNC) passive sampler, has been shown to correlate well against active samplers within indoor environments.[34] After a sample has been collected, it can be examined using an optical or electron microscope to determine the number, size, shape and structure of the particles collected. This data can then be used to calculate the Pnum and Psd that the sampler was exposed to.[33,35–37] This method uses a scanning electron or optical microscope and automated image analysis. Unfortunately, gravimetric sample analysis is labor intensive and cannot be used to measure UFPs (<0.1μm) which are too small to be observed. There are also inherent errors in particle size and surface area measurements due to estimating 3D properties of particles from 2D images.

Passive gravimetric samplers are extremely small (1.5-5cm diameter) and light (1-5 grams) and require no maintenance. These samplers can be deployed for both long and short periods, however, this is subject to the ambient concentrations as the sensors can have too few or too many particles deposited for the automated image analysis to be effective. If the samplers are operated in especially low PM environments, or for very short periods, this requires more scanning electron microscope (SEM) images to be analyzed to determine an accurate concentration. With gravimetric samplers the chemical composition of particles can be acquired using instrumental neutron activation analysis (INAA), particle-induced X-ray emissions (PIXE) or other processes, although this can be time-consuming, expensive and specialized.

Impactors can separate particles based on their inertia, and this allows for measurement of a mass-based size distribution. The most commonly used type of Impactor is the Cascade Impactor, in which particles flow through a series of sections (typically 3 to 15),[15] each containing an impaction plate. In each section, particles above a certain size cut-off are deposited onto the impaction plate. Between each stage the diameter of orifices decreases, which leads to increased velocity of the aerosol and impaction of progressively smaller particle sizes. The Cascade Impactor is made up of several stages followed by a final filter, which collects any particles that were not deposited in any of the previous stages. Conventional Cascade Impactors cannot size particles <400nm, however some Low-Pressure Cascade Impactors can size particles from 30nm upwards, for example, the electrical low pressure impactor (ELPI) which can provide size distributions in real-time.[15,38] The collection substrates can be removed from the Cascade Impactor and are processed in the same ways as standard gravimetric filters.

Optical methods are based on the interactions of particles with light. When light hits a particle, it is either scattered or absorbed. Optical methods are based on the principle of measuring scattering, absorption and extinction (the sum of scattering and absorption) to determine the particle concentrations of an aerosol.[38] Scattering Laser Photometers measure the intensity of scattered light in one or more directions using a photometer detector; the combined intensity of scattered light is directly proportional to the volume concentration of the aerosol within the optical volume.[39] Photometers collect real time measurements with a frequency of 1s, and measure particles from ~40-100nm upwards, however, measurement efficiencies are significantly lower at smaller particle sizes. They are commonly used with impactors or cyclones to measure PM_1, $PM_{2.5}$, PM_{10} or the respirable aerosol fraction and are extremely popular due to their small, portable, robust and reliable nature. Photometers can measure accurately over a larger range of Pmass concentrations (0.001-200 mg/m^3), making them suitable for both clean and highly polluted environments. Examples of commercial photometers include the DustTrak, DataRAM 4 and UCB-PATS.

Gravimetric samplers are more accurate than optical methods since they measure PM directly rather than indirectly. Therefore, at the start of campaigns, optical Pmass sensors are often co-located with gravimetric samplers to be calibrated.[40] Optical measurements vary depending on the optical properties of particles, and therefore do not provide absolute mass concentrations.[41] However, there is a significant trade-off as gravimetric filters are labor intensive and not real-time. When using gravimetric filters to measure Pmass, the samples need to be dried and weighed and then chemical testing requires additional labor. In addition, the process of drying the filters can remove the more volatile compounds, affecting the mass measurement. Collecting data on Pnum, Psd, particle shape, particle surface area and particle structure requires use of a scanning electron microscope, however, automation has made this process less labor intensive.

Particle Number

Pnum is measured using optical and current methods. Optical Particle Counters (OPCs) work similarly to a scattering laser photometer with a diode laser shining on the optical volume with the scattered flash being measured by a photodetector; unlike photometers, only one particle is illuminated at once. The photodetector converts the flash of light into an electrical current, and as each electrical current corresponds to a different particle, the number of particles can be counted. The size of the particle is proportional to the intensity of the flash and electrical current generated, so using a calibration curve particles can be sized based on the amplitude of the current generated.[38] For example, the Alphasense OPC can count particles with a diameter of 0.35-<40µm and place them into 24 size categories, with a sampling frequency of 1s upwards. Other OPCs include the TSI Optical Particle Sizer 3330 and GRIMM OPC. OPCs are light, portable, rugged and quiet, however their main disadvantage is their inability to count particles <300nm. Particles smaller than this cannot be counted by the optics, hence are grown to a size where they can be counted in the CPC (described below). Particles <300nm in size make a substantial contribution to total Pnum concentrations.

Condensation Particle Counters (CPCs) share similar operating principles to OPCs but can count particles of much smaller sizes. CPCs condense a solvent (typically butanol, isopropyl alcohol, or more recently water) onto the surface of particles to grow them to a size where they can be counted. Once grown, the particles pass through the focal point of the laser beam and are individually counted. Vapor around the particles needs to reach a certain degree of super-saturation before condensation occurs, and the magnitude of this super-saturation determines the minimum countable size of the CPC. There are two types of CPCs; Full Flow CPCs (sometimes called Continuous Flow Laminar CPCs) and Mixing CPCs (sometimes called Fast CPCs). In Full Flow CPCs the aerosol is drawn through a conditioner where it is saturated with vapor and brought to thermal equilibrium. The aerosol then passes into a cooler growth tube where the liquid is condensed onto the surface of particles. Full Flow CPCs require higher regulation of temperature control than other CPCs. In aerosol research the Full Flow CPC is the most commonly used due to its robust and reliable nature,[42] however, they have a relatively low sampling frequency (several seconds) due to zones of recirculation and time needed to establish super-saturation.

Many of the atmospheric processes measured by CPCs are rapid and therefore there is a need to develop a CPC capable of higher frequency sampling. Mixing CPCs were developed in the 1980s to increase the temporal resolution of measurements.[43] In a Mixing CPC, a cold aerosol flow is mixed with a warm saturated gas flow; this dilutes the aerosol flow, allowing the CPC to cope with the dynamic range of indoor Pnum. When this was designed it was able to achieve mixing times as fast as 0.6s, 10 times faster than any commercially available full flow CPC.[42] Therefore, Mixing CPCs are sometimes referred to as Fast CPCs. One of the main uses of a Mixing CPC is as part of a Scanning Mobility Particle Sizer (SMPS) (described below), which measures particle size distributions. SMPS's commonly have a scan time of 2-4 minutes and this is mainly limited by the slow temporal resolution of the CPC. Under certain conditions a "Fast CPC" could capture data at 3s.[44] However, realistically, scans are unlikely to be reduced below 30s. Currently, Full Flow CPCs and Mixing CPCs have temporal resolutions of 0.25-3s and 16-100ms respectively.[42] The detection limit, or "cut-off", of a CPC is described by its 50% detection efficiency diameter (d_{50}); the size at which <50% of particles passing through the CPC are counted. Changing the temperatures within the condenser and saturator can change the D_{50} of a CPC. Handheld CPCs can make counting errors when multiple particles are located together in the optical detection region, and this is a common occurrence for concentrations >250000 particles/cm^3. CPCs need to be maintained level, to prevent the working fluid entering the optical circuitry and this makes them difficult to use for personal exposure monitoring.[45]

The Diffusion Size Classifier (DiSC) can estimate Pnum, the average particle diameter in the size range of 10-700nm and LDSA. In the DiSC the aerosol is charged in a unipolar diffusion charger and then passes through two electrometer stages. The DiSC is one type of Diffusion Charger, primed to be important in the future of UFP measurement due to its ability to measure surface-area related metrics. The first stage or "diffusion stage" consists of a stack of stainless-steel screens connected to sensitive electrometers; the second stage is a HEPA filter connected to an electrometer. Deposition of particles in each of these areas generates a current; $I_{diffusion}$ and I_{filter}. The relationship between these generated currents can be used to calculate the Pnum and average particle diameter.[46,47] The DiSC is small, portable and battery operated, and this makes it highly suitable for field measurements. The DiSC performs very well for its size and cost but is significantly less accurate than the larger and more expensive CPC and SMPS. Although the accuracy is generally good, the DiSC can perform poorly under certain conditions; for example, measuring monodisperse aerosols of specific compositions and sizes. This is because larger particles can carry more charge which leads to overcounting.[45] When compared to the SMPS and CPC the mean particle size and Pnum were within ±30% and ±50% of reference values, respectively.[48] They identified that the presence of particles >400nm drastically bias the mean particle size measurement. An example of this piece of equipment is the TESTO DiSCmini. Traditionally, DiSCs are cheaper than CPCs; however new periodic technical inspection regulations for vehicle emissions are being introduced in Germany, with 35,000 garages mandated to have Pnum sensors by the 1st January 2021.[49] This large demand will drive the market to produce low-cost (<$5000), reliable and easy to use Pnum measurement devices. The likely result will be that DiSCs and CPCs will be forced to become competitive on price, which will likely increase their widespread use in other sectors, for example, IAQ measurement.

Particle Size Distribution

Psd can be obtained from SMPS, Fast Mobility Particle Sizer (FMPS), OPCs, APSs and passive air samplers. In Differential Mobility Analyzers (DMA) particles are given a unipolar corona charge and are passed through an electric mobility analyzer; from here particles of a given diameter are selected based on their electrical mobility.[39] The size selected by the DMA is determined by the magnitude of the voltage applied. Exponentially increasing the voltage allows scanning through a particle diameter size range in several minutes. The same concept underpins operation of the SMPS. An Electrostatic Classifier is a particle neutralizer combined with a DMA; it can generate and subsequently size select particles. A SMPS is essentially an Electrostatic Classifier connected in-line with a CPC; in this system the Electrostatic Classifier selects particles of a given size, and the CPC counts these particles. The SMPS is the most precise instrument for measuring particle size distributions. The FMPS differs from the SMPS by using an Electrostatic Classifier and multiple low noise electrometers to measure Pnum and Psd in the 5-600nm range. The benefit of this over the SMPS is a 1s sampling frequency, making it more suitable for measuring rapid aerosol processes. However, the SMPS measures the very smallest particles with a higher accuracy than the FMPS. Examples of this equipment include TSI's SMPS 3938 and FMPS 3091. The SMPS with a range of 1-1000nm is often paired with an Aerodynamic Particle Sizer (APS) with a range of 0.5-20µm when Pnum and Psd of particles >1000nm are also of interest.

The APS uses the inertia of particles to determine their size; firstly, the aerosol flow is constricted through a nozzle and this accelerates the aerosol. The velocity of the particle can then be related to the particle's surface area and mass and therefore aerodynamic diameter. The aerodynamic diameter is determined assuming spherical particles and uniform density. Secondly, particles then pass through two laser beams separated by 200µm; as the particle passes through each beam, light is scattered onto a photodetector. The time difference detected between the two pulses of scattered light can be used to determine the velocity and therefore aerodynamic diameter. The magnitude of the electrical current generated by the scattered light also provides a secondary estimate of the particle size. APSs are commonly operated alongside a SMPS but can be used exclusively when particles <500nm are not of interest. For example, APS measurements are suitable for source characterization of resuspended material.

Particle Surface Area

Active particle surface area is an important metric in the future of UFP measurement and can be measured by Diffusion Chargers, specifically NSAMs.

Diffusion Chargers use corona discharge to create unipolar ions that diffuse onto the active surface of particles, and an electrometer then measures the charge that is transferred from the ions to the particle. This charge can be related to the active surface concentration, which is a fraction of the geometric surface area. This is a similar measurement premise to the DiSC. The nanoparticle surface area monitor (NSAM) measures particles between 20-400nm using the principle of unipolar diffusion charging.[50] It can measure lung-deposited particle surface area concentrations, based on lung particle deposition models.

Table 2 summarizes the key properties of each of these sensors with their advantages and disadvantages.

	Equipment	Real Time (Time Resolution)	Portability	Size Range	Detection Limits	Price Catagory (1 Lowest - 5 Highest)	Advantages	Disadvantages
Particle Mass	Gravimetric Filters	No	High	150nm<	10µg/m^3<	1	Filters can be used to determine mass and number concentrations, size distribution and composition. Cheap and simple to deploy indoors.	Processing the filters is highly time consuming
	Photometer	Yes (1s)	High	(40-100nm)-10µm	0.001-200mg/m^3	1-2	Portable, reliable, accurate and relatively cheap.	Not a direct measure of PM
	Low-cost photometers	Yes (1s)	Very High	N/A	0-600µg/m^3	1	Low-cost and high portability	Is not a self-sufficient sensor, it needs to be built into a system with a computer. Low sensitivity, especially at low concentrations.
Particle Number	CPC (Full Flow)	Yes (3s)	Medium	2.5-15nm<	<1x10^4-1x10^6 particles/cm^3	2-3	Highly robust and reliable equipment. Regulatory compliant in vehicle emission measurement due to a longer standing history of use.	Lower time resolution than mixing CPCs. More likely to have optics contaminated by working fluid than mixing CPC
	CPC (Mixing)	Yes (0.5s)	Medium	2.5-15nm<	<1x10^4-1x10^6 particles/cm^3	2-3	Higher time resolution than mixing CPCs, important for rapid atmospheric processes. Can measure higher concentrations due to inbuilt dilution.	More complicated to accurately measure sample flow,
	OPC	Yes (1s)	High	0.3-20µm	<1x10^4 particles/cm^3	1-2	Lower cost and more portable than conventional CPCs.	Unable to measure the smallest particles (<0.3µm).
	DiSC	Yes (1s)	High	10-700nm	<5x10^2-1x10^6 particles/cm^3	1-3	Portable, reliable, robust and lightweight. Accuracy is within 15-20% of a reference CPC. Can determine average diameter of measured particles (accuracy with 30% of SMPS).	Less accurate than CPCs, is not directly counting particles. Accuracy is good, but can be poor for certain particle compositions and shapes.
Particle Size Distribution	Impactors	No	Variable	1µm-10µm	N/A	1-2	Useful when looking at the size specific chemical characteristics of aerosols.	Not useful for smaller, or ultrafine particles. Sample analysis is time consuming.
	SMPS	Yes (1-4 mins)	Low	2.5-1000nm	1-1x10^7 particles/cm^3	4-5	Provides the highest resolution size distribution of particles .	Much lower time resolution than an FMPS
	APS	Yes (10s)	Medium	0.5-20µm	1000 particles/cm^3	3-4	High Temporal resolution, and can be used to suppliment equipment unable to measure at the larger sizes	Unable to measure the smallest particles (<0.5µm).
	FMPS	Yes (1s)	Low	5-560nm	N/A	4-5	No radioactive source. Much higher time resolution than an SMPS.	Size distribution generated has a lower resolution than a SMPS (30 channels vs 190 channels). Electrometers provide les accurate particle number concentrations tan the CPC used in the SMPS
Particle Surface Area	NSAM	Yes (1s)	High	10-1000nm	<10000 µm^2/cm^3	2-3	Portable, able to measure LDSA.	High sensitivity to environmental variables

368 **Table 2.** A comparison of the properties of PM sensors.

4. Experimental Applications

This section outlines the experimental applications of the previously described technologies, and aims to provide insight into the practicalities of deploying these indoors.

Compliance Measurement, Temporal Trends and Source Apportionment

Compliance measurements are commonly collected when it is necessary to understand how the severity of pollution relates to national and international standards and to historical measurements, usually making Pmass the focal metric. Many of these studies use real-time measurements and therefore often contain sections devoted to temporal variations in PM and apportioning these variations to potential sources.

One cheap and robust method for testing compliance is by using gravimetric aerosol samplers; however, these are not real time and therefore cannot be used to identify short-term temporal variation. Passive aerosol samplers have been used in primary schools, with polycarbonate and quartz filters deployed at child breathing height (1.2m).[51] This study demonstrates that long-term temporal variations can be measured using gravimetric samplers deployed and collected over several seasons.[51] They were also able to apportion sources using chemical analysis, with particular sources having distinctive chemical compositions.[51] Passive samplers are smaller and quieter than larger active samplers and so are appropriate for use in schools, many workplaces and homes.

Cascade Impactors can be used upstream of traditional gravimetric samplers when the mass-based particle distribution is of interest. For example, cascade impactors were used to simultaneously sample particles of >10μm, 10-2.5μm, 2.5-1μm and <1μm in 8 different indoor locations in France.[52] This included private residences, a school and a restaurant across a range of urban, suburban and rural settings. The particles were chemically analyzed to determine the concentrations of 16 US-EPA priority Polycyclic Aromatic Hydrocarbons (PAHs). Gravimetric samplers are also a relatively unobtrusive method of sampling, for example, size segregated Pmass was measured in a well-ventilated primary school gym during PE lessons, using personal cascade impactors to minimize intrusiveness and health and safety risks.[53]

NSAMs are used to account for UFP exposure by measuring LDSA. When measuring UFP exposure and dosing, LDSA is often chosen because it is likely a better indicator of health effects than other metrics. For example, exposures were measured in four elderly care centers, with spatial and temporal distributions of LDSA being assessed.[54]

Major sources are typically identified through chemical composition, but sources can also be apportioned through temporal measurements, although this is less accurate, and speculative. For example, apportioning increases in PM during rush hour traffic periods to vehicular emissions. A DustTrak was used to measure PM_{10} in Hong Kong schools to assess compliance against Hong Kong's Air Quality Objectives, with increased levels of PM attributed to sources such as traffic and construction.[55]

When measuring compliance, it is important to consider whether a device is suitable for the levels of PM being measured; some sensors cannot detect low levels of PM whilst others cannot detect high levels of PM. For example, photometers were used to measure Pmass in highly polluted, densely populated, low income housing in urban Dhaka, Bangladesh.[56] The photometers were converted from smoke detectors and were developed specifically to measure in high pollution environments, with a lower detection limit of 50μg/m^3. However, this caused difficulties with 49% of $PM_{2.5}$ measurements falling at or below 50μg/m^3.

Indoor vs Outdoor Comparisons

Indoor vs Outdoor studies are usually focused on understanding the contributions of outdoor air to IAQ, the penetration rates of particulates and how ventilation and building design may improve or worsen IAQ. In addition, air pollution generated within households can have significant influence on ambient air pollution concentrations, for example, in Los Angeles, consumer volatile chemical products are the largest source of ambient VOCs.[57] These studies are not limited to use of any specific metric, in fact, each metric adds different value and should be selected based on the specifics of the investigation.

For example, the influence of outdoor air pollution and smoking on indoor $PM_{2.5}$ and Black Carbon levels was quantified in 21 industrial community homes in Pittsburgh.[58] The Personal Exposure Monitors (gravimetric filters) needed to be replaced every 3 days to prevent particle overload on the impaction plate or perturbation of the size cut-off inlet. The samplers were placed in the main activity room away from the windows, and heating and combustion sources to try to ensure the samples were representative of the whole room. Gravimetric samplers were chosen because industrial particle emissions are mainly composed of larger sized particles, contributing more to particle mass.

Indoor, outdoor and personal exposure samples were collected for 6 Beijing residences whilst operating air purifiers.[59] Gravimetric sampling was chosen because the researchers wanted to chemically quantify various health-related chemical components; they compared the indoor/outdoor ratios of 27 chemical species.

The SMPS is often the equipment of choice in investigations aiming to understand indoor penetration and deposition behavior. This is because these processes are determined by particle size, which can be measured by the SMPS. For example a SMPS and APS were used to measure both indoor and outdoor Psd simultaneously by alternating between indoor and outdoor air inputs using a specially designed sampling manifold.[60] A similar study was conducted in modern offices.[24] In this investigation they were able to determine differential infiltration and deposition as a function of size. Indoor and outdoor Pnum and Psd were measured simultaneously in a school using two SMPS units; they were able to identify the main sources influencing indoor PM and determine indoor/outdoor ratios as a function of size.[61]

Another study used an OPC, CPC and gravimetric samplers simultaneously; the OPCs size distribution was used to supplement the absolute Pnum measurements of the water-based CPC.[62] With the water-based CPC also having a maximum size cut-off of 3μm, the OPC was able to extend this range up to 10μm. This study aimed to understand indoor and outdoor source contributions to indoor air over different size ranges, so the OPC was important to measure the size distributions. OPCs provides a more affordable and portable measurement of Psd than the SMPS, but lack in the ability to measure <300nm.

Our current understanding of the relationship between indoor and outdoor PM is summarized by Chen[63].

Source Characterization

Source Characterization investigations aim to quantify the particle generation of various PM sources within the indoor environment. This can be studied in a real-world, laboratory or chamber environment, predominantly using Pmass, Pnum and Psd metrics and real-time measurement equipment.

In a chamber setup fine and UFP emissions were measured from 13 particle sources using an OPC and CPC.[64] A total-capture dilution tunnel system was used to investigate the Pnum and Psd emissions for 11 household cook stove-fuel systems using a SMPS.[65] Conversely, cooking was characterized using a SMPS and APS in the real world, namely in 15 homes in Brisbane, Australia.[66] Elevated Pnum was linked to 21 other indoor activities using occupant logs and these events were measured using a CPC and Dustrak. Controlled environments allow for more accurate and repeatable measurement of particle generation, but real-world measurement can provide a more realistic basis for investigating processes; for example, dispersion, ageing and deposition of PM.

OPCs are ideally suited to resuspension studies because they negate the OPCs biggest weakness, the inability to measure particles <300nm. This is because the process of resuspension by human activities contributes most to the coarse particle fraction (>1µm).[66] OPCs are commonly used when the UFP fraction is not of interest or to supplement the measurements made by other equipment. OPC measurements can add Pnum and Psd data to data collected by CPCs and photometers. Alternatively, at additional cost, the OPC could be paired with a diffusion size classifier to measure a much wider range of 10nm-20µm. Of 13 studies measuring resuspended particles and how they varied in size between different human activities, 8 utilized OPCs and 3 utilized APS.[67]

When high time resolution data is important, a FMPS may be used rather than a SMPS. For example, a FMPS (5.6-560nm) and OPC (0.3-20µm) were used to characterize the emissions from seven wood burning fireplaces in German homes.[68] Although these fireplaces largely have airtight seals, the combustion chamber needs to be opened regularly to put more wood in and this led to increased Pnum concentrations within the room. As the chamber only remains open for a few seconds, a shorter time resolution is required than the >1-minute resolution of the SMPS. Therefore, the researchers used a FMPS to measure Pnum and Psd at 1s resolution. The nanoparticle emissions of burning incense were characterized using a FMPS within a chamber.[69] High time resolution data was important to understand periods of rapid change, for example the post-burning period after the incense was extinguished.

High Resolution Spatial and Temporal Measurements

It is becoming increasingly important to understand the lateral PM variations within rooms and buildings, to link sources, ventilation and purification systems. Therefore, there is a need for low-cost, portable real-time sensors. It appears like the flagship measurement type for this will be photometry, with the majority of developed low-cost sensors working on the light scattering principle.[70] However these investigations are currently still largely testing the premise, it remains to be seen whether these instruments are sufficiently accurate and sensitive. For example, several of these photometers were deployed in a single room to determine lateral variations in PM.[71] Similarly, these sensors have been deployed in households in Raipur, India to understand the spatiotemporal resolution of PM generated by cookstoves.[41] In lab tests the sensors agree well with reference grade equipment, however, these sensors become saturated at 4-5mg/m^3 compared to the 20 mg/m^3 of the SidePak, making them less suitable for high pollution environments.[72]

5. Discussion

Whether it is important to measure multiple metrics in an investigation depends upon the study design, purpose and focus is. Using a variety of instruments, which, measure the same or different metrics will improve confidence in results and understanding of the nature of indoor PM. For example, in photometer-based studies photometers are regularly co-located with reference grade gravimetric samplers to ensure the data collected is of suitable accuracy or to calibrate the photometer if necessary. With Pnum and Psd measurement, it is important to consider whether it is possible to expand the particle diameter range measured by using a number of different pieces of equipment. For example, supplementing the SMPS (2.5-1000nm) or FMPS (5-560nm) with use of an APS (0.5-20μm) or OPC (0.3-20μm). Combining use of high cost, less portable and more accurate equipment with low-cost, highly portable equipment can also improve spatial mapping results. This is important, because air pollution is not homogeneous throughout a single room or building. Given the disparity between the concentrations of PM indoors in LEDCs, and higher economically developed countries (HEDCs) (responsible for ~97% and 3% of premature deaths due to household air pollution in 2016),[3] it is essential to be aware of the range limitations of sensors. For example, many low-cost photometers are able to measure effectively in high concentration environments, but are too insensitive to use at low concentrations.[72] Conversely, mixing CPCs and photometers are extremely versatile in measuring a wide dynamic range, with sensitivity at low concentrations and with inundation only at very high concentrations. This is due to the mixing CPCs dilution of the aerosol flow and the photometers historical use for occupational health monitoring in high pollution environments, (e.g. in saw and flour mills).

Challenges of PM metrics

A challenge of the Pnum/Psd/Surface area metrics are the difficulty in comparing measured values across literature. Different investigations often operate equipment with differing size ranges or operate the same piece of equipment at different size ranges. Unfortunately, comparing measurements of different size ranges is not meaningful.[8] In this review paper, even the difference in minimum diameter measurement between 6-15nm made reliable comparisons difficult and therefore only two out of the eight studies included were directly comparable. Having no standardized size range is one of the reasons why universal standards have not yet been developed. Different types of Pnum and Psd sensor have highly variable size ranges depending on the method being implemented; this adds further complexity to the task. Without regulation, expecting original equipment manufacturers (OEMs) to comply to standardized size ranges is difficult as they will want freedom to change and increase their size ranges as technology improves. On the other hand, OEMs like regulation-backed markets because it mandates the need for their products. It will be important to allow OEMs to contribute to discussions around standardization. Being unable to directly compare to other literature or universal standards, investigations instead must rely on internal comparisons, for example, the levels were *x* times greater than background levels or Site A was *x* relative to Site B. Although there are standards issued for the Pmass metric, very few are specific to indoor environments and this is a problem because the variability in concentration, chemical composition and Psd can all be significantly different to outdoor environments. This is because indoor air is made up of contributions from both indoor and outdoor sources; this means that although they share many physico-chemical properties, they are often far from homogenous.[8] Future campaigns should aim to deploy high grade sensors to measure the physio-chemical properties of IAP under a variety of scenarios; one such campaign is HOMEchem.[73] HOMEchem is a collaborative field investigation aiming to determine how everyday activities effect the emissions, interactions and removal processes of particles and trace gases in indoor environments.[74] Once the nature of IAQ is better understood it can be compared to outdoor air quality in order to make informed decisions on whether health standards should differ between them.

Standardizing the field of PM measurement

Given the difficulty in making comparable measurements, there is a need for the community to come together and to work towards standardized measurements. Accordingly, there are two types of guidelines that need to be defined: 1) standardized size ranges or D_{50s} for individual measurement techniques e.g. CPCs, OPCs, DiSCs and NSAMs, and 2) regulatory guidelines for what are allowable concentrations of PM for these standardized size ranges.

However, setting these guidelines is not an easy task (especially No. 2), and therefore, a model for developing improved guidelines is illustrated in Figure 1.

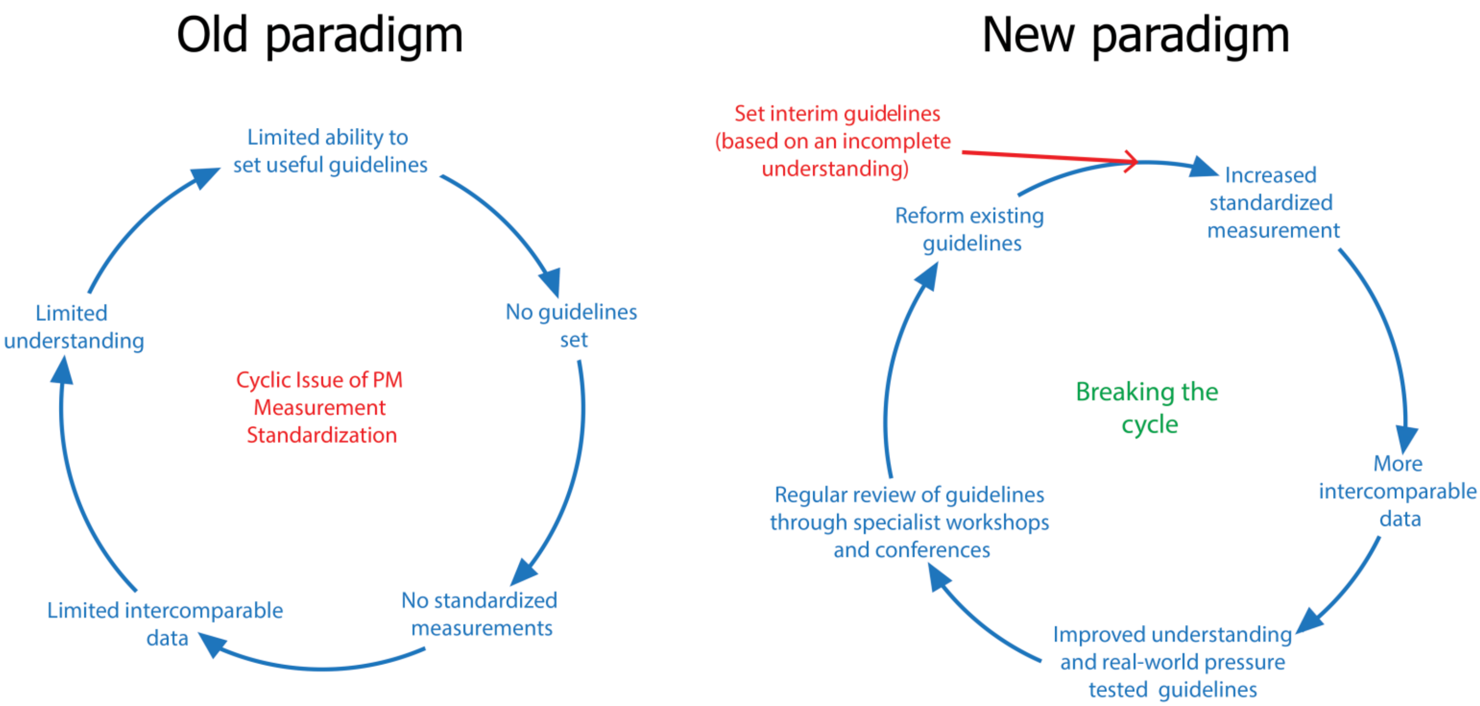

Figure 1. The cyclic issue of PM Measurement standardization and breaking the cycle.

Initially, due to our limited understanding of the epidemiology of Pnum and surface area concentrations, regulatory guidelines are difficult to relate to health effects, as is the case for existing Pmass guidelines. Instead, good, satisfactory, poor and extremely poor standards, could be based on the frequency of measurement, i.e. based on measurement frequency distributions as opposed to a mechanistic relationship to health effects. As the "new paradigm" cycle continues and epidemiological understanding improves, we could start to implement the more useful health related guidelines.

Development of these guidelines are beneficial to a variety of stakeholders. Firstly, PM researchers and epidemiologists will have more inter-comparable measurements, which will improve understanding on their respective fields. Regulators will be better informed, allowing for development of more robust guidelines. This will expand the usefulness of Pnum, Psd and surface area metrics for regulatory purposes, and this in turn will benefit equipment manufacturers by increasing demand for their products. Some other broader challenges associated with aerosol science community are addressed by Sorensen.[75]

The relationship between IAQ and energy efficiency

In recent years improvements to the energy efficiency of buildings has reduced air exchange rates between indoors and outdoors, to improve energy efficiency through reducing heat losses. However, this has created indoor environments where pollution can become "trapped" and accumulate to much higher levels than before.[10] A balance is needed between improving energy efficiency, reducing operation costs and improving IAQ.[76] However, in some environments such as in the mega-cities of many LEDCs, reducing the exchange between indoor and outdoor air may improve the IAQ, especially in indoor environments without dominant sources of IAP. Improved energy efficiency may motivate increased research on IAQ, how it relates to outdoor air quality and the nature of indoor air pollutants ageing indoors. It is worth noting that indoor air chemistry will have similar complexity to ambient atmospheric chemistry. Some of the most important questions relating to IAQ and "green buildings" are addressed by Steinemann.[77]

Low-cost sensors

Low-cost sensors are becoming increasingly important in the modern world and are essential to improving the spatial and temporal resolution of urban air pollution measurements.[13,78] Static and sparse air pollution monitoring stations are not sufficient to fully understand the behavior of pollution in urban areas. Existing networks could be supplemented with a low-cost high-density network. The same concept applies indoors, but on a smaller scale; by taking a single measurement in a room or building the assumption is that the air is homogenous and the spatio-temporal variation is neglected, introducing errors into exposure intake estimations.[71] It is worth noting however, that even high resolution spatio-temporal measurements may not be fully indicative of individual exposure given the "personal cloud" effect,[79] therefore, in the future low-cost sensors will also be needed for personal exposure measurements. Switching from wired to wireless data transmission has been shown to reduce initial investment and annual operation cost by 3x and 5x, respectively, in the US.[75,80] Wireless data transmission also allows for unattended large-scale monitoring. Wireless data transmission is especially important for indoor data collection because minimizing intrusiveness is important. Intrusion into residences and workplaces can be disruptive, and being able to minimize intrusion will increase the participation in projects. Furthermore, in unoccupied environments, intrusions can influence indoor PM through resuspension. Some of the issues currently associated with the future of low-cost sensor networks are the consistency and durability of sensors, the reliability of data and the high costs associated with data processing. Moreover, most low-cost sensors have a short lifetime of 6 months to a few years, which will need to be improved for these sensors to be viable in the future. The costs of calibration, servicing (replacing batteries), integrating the sensor into a device and data processing often exceeds the cost of the sensors themselves; these costs need to be reduced. Sensor performance will need to be tested under a wide range of environmental conditions before they are ready to be deployed on a large scale. Gas sensors are being miniaturized at a much faster rate than particle monitors, largely because it is difficult to develop particle monitors that are very sensitive to small concentrations.[80] Moreover, with gas sensors, the focus is purely on concentration, while with PM it is important to understand Pnum, Pmass, Psd and chemical composition. This makes PM a lot more difficult to effectively quantify than ambient gas concentrations. Another shortcoming of low-cost devices is their signal to noise ratio, making them much less useful in low pollution environments. This can be negated to some extent by recording for longer periods and averaging the results, or by co-locating several sensors and taking an average. Digital filters are commonly applied to the data from these sensors to remove high-frequency noise.[71]

Applications of and Considerations for Low-cost sensors

In cities, creating networks like this may be made easier due to existing infrastructure, mainly access to fast reliable internet. However, some of the worst air pollution is experienced in rural low-income areas where networks would be difficult to set-up and maintain. In addition, low-cost sensors are increasingly important in making measurements in LEDCs due to their nature of being easily deployed and operated and having low power requirements. Moreover, with PM concentrations usually higher in LEDCs, the decreased sensitivity at low concentrations is less of a problem. A summary of low-cost sensors and monitors is available, however, these are neither specific to indoor or outdoor environments.[70]

If low-cost sensor networks are introduced nationally and a large database is generated, several issues need to be considered. It is important that the data collected is easily accessible to interested stakeholders, and that the database is not held by a private company that might misuse it for financial gain.[80] It is necessary to consider who would own such a network and database; public bodies, research bodies, commercial entities or citizens. Minimizing the need for data processing and analysis through automation could make air pollution data from portable sensors more accessible to the public. If the data can be interpreted into an easily accessible form, then citizen uptake will increase. Fortunately, low-cost sensors require very little knowledge to be deployed and require less technical maintenance than more complicated equipment, which may also increase citizen uptake. Low-cost sensors could also provide immediate value, by warning occupants of high pollution levels and offering suggestions to mitigate these, for example, opening the window or automatically turning on an air purifier. It is also worth considering whether it is essential for these low-cost sensors to perform well at low-concentrations; if their primary purpose is to inform users in real time of dangerously high levels. People may be more inclined to remediate IAQ problems based on personalized measurements of IAQ, rather than city wide pollution measurements and warning systems.

Ethical concerns of real-time measurement

Real time measurement within residences also raises various ethical concerns. For example, IAQ data can be used to infer activity, such as when the house is occupied or unoccupied, whether residents are awake or asleep and whether activities such as cooking, or bathing are occurring. Therefore, personal data is inadvertently collected alongside the IAQ data. This needs to be considered when viewing the data in real-time and ensuring anonymity when viewing data afterwards. A further ethical concern occurs if dangerously high pollutant levels are observed in real time. What level of responsibility and duty of care should residents expect? Should looking at results in real-time be avoided completely, even though this is an important part of maintaining sensors and troubleshooting?

6. Conclusions and recommendations

Pmass is the most widely used metric of PM currently with measurements being robust, reliable, and easily compared to well defined standards and a long-standing literature. However, specific indoor health related standards are still to be developed. Pmass will remain useful due to its long history of use in compliance testing; however, future epidemiological studies may conclude that Pmass has less correlation to human health effects than other metrics. Pmass is likely to continue its evolution from PM_{10} and $PM_{2.5}$ down to PM_1 or $PM_{0.5}$ as technology improves. The dominant contribution to Pmass comes from larger particles (>100nm), whereas Pnum is largely influenced by the smallest particles (<100nm). The Pnum metric is becoming increasingly useful as focus is shifting towards measurement of UFPs. However, with Pnum it is very difficult to make comparisons to previous studies and it seems unlikely that any air quality standards will be developed soon. The Pnum metric is considered a better determinant of health effects than Pmass,[26] but Pmass sensors are being reduced in size at a much faster rate than Pnum sensors. This might make Pmass sensors the preferable choice for the low-cost sensor networks of the future. Although Pnum sensors such as OPCs are being reduced in size, they cannot measure the very smallest particle sizes. The Psd metric can allow for observations that cannot be determined from Pmass or Pnum alone and will become increasingly implemented as sensors improve. Psd will likely remain as a "research grade" measurement, solely for understanding the nature of PM and applying that to developing better metrics and sensors for compliance monitoring. There is consensus that future UFP metrics should provide insight into how PM interacts with the body through intake, uptake and transport. Therefore, many researchers are favoring a surface area related metric, which correlates better with toxicological or biological activity than either Pmass or Pnum.[30] NSAMs are likely to become an increasingly important measurement option, as interest in measuring surface area related metrics increases.

Many countries and organizations are having to decide whether to solely legislate using the historical and conventional Pmass metric or to adopt other metrics. However, this is an extremely difficult task given the current lack of understanding of PM and its associated health effects, even though PM is one of the best understood forms of air pollution, there is still much that needs to be understood. Several essential epidemiological questions still need to be answered.[81] Firstly, which properties, or combination of properties, are the most important determinants of potency; for example, size, surface area, or chemical composition. Secondly, are chronic background pollution levels or acute high-level pollution events a greater determinant of health effects. This will largely inform what type of standard should be enforced; for example, daily average or "should not exceed *x* for longer than *y* duration". It will also inform the needs of regulatory compliance measurements, for example, if high level pollution events are deemed the most important determinant of health effects, then having PM monitors which are sensitive to low concentrations is far less important. Until these questions are answered, we should continue to experiment using a wide range of metrics to better understand the nature of PM.

With low-cost real-time sensors at the forefront of meeting rapidly increasing public interest, and with citizen science projects becoming more frequent, personalized information about IAQ is likely to become increasing available.[13,82] Eventually this could lead to real-time IAQ warning systems in homes; allowing residents to more easily mitigate IAQ issues.[82] This level of technology would also allow us to resolve many of the issues related to IAQ and energy efficiency. As real-time low-cost sensors become increasingly common, high spatial distribution measurements which were previously difficult are likely to become more common. However, it is unlikely that the current generation of low-cost PM sensors will be able to detect subtle variations in the indoor environment. But this will likely change as sensors are periodically improved. To fully understand the future of PM measurement, it is essential to understand how PM interacts with health, and which metrics are best able to capture this interaction.[81] A better understanding of epidemiology will inform the future of compliance measurement and source characterization in indoor environments.

Many premature deaths worldwide are attributed to indoor PM. Several essential metrics and measurements techniques are available that practitioners and scientists can use to better understand and reduce indoor PM. In the future it is essential to better understand what PM properties most strongly effect health and to channel this information into the development of improved metrics, measurement techniques, legislative standards and new experimental applications.

Words: 9400 + (2 Tables + 1 Figure) = 10000

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