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Building and Environment 216 (2022) 108992

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Ultrafine particles: A review about their health effects, presence, generation, and measurement in indoor environments

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ARTICLE INFO

Keywords:
Ultrafine particles
Indoor aerosol
Health effects of particulate matter
UFP indoor generation
Particle detection limit
Differential mobility analyzing system measurements

ABSTRACT

Human exposure to aerosols has been associated with diseases and death, reducing the population's life expectancy up to a few years. Indoor particulate matter is predominant in determining human exposure to PM because people spend most of their time indoors.

Ultrafine particles (UFP) impact the human body differently from $PM_{2.5}$ or PM_{10} fractions. Therefore, scientists cannot apply the same approach to assess the effects of UFP and PM on human health.

This work summarizes the health effects, generation, and measurement of ultrafine particles in indoor environments through a literature review. When indoor particle generation is low, particle concentration indoors depends strongly on outdoor aerosols, with an indoor-to-outdoor ratio below 1. In buildings with a high indoor particle generation, the average indoor-to-outdoor UFP concentration ratio can reach 14. Combustion, electric heating, and house cleaning are the main generators of UFP indoors.

Current standards for UFP assessments do not provide a solid ground for accurate and reliable measurements. Moreover, the lowest detection limit of instruments used to measure UFP concentration can be significantly different while also showing poor repeatability even among instruments with the same manufacturer and model. Consequently, data supplied by studies on UFP health effects are insufficient and inconclusive.

Using ultrafine portable monitors would allow determining properly human exposure to $PM_{0.1}$, but such instruments are expensive for wide use. Since there is a good correlation between UFP and NO_X data, low-cost NO_X sensors are good candidates to create a dense and accurate monitoring network of UFP, including indoor environments.

1. Introduction

Short-term and long-term human exposure to aerosols has been correlated with high toxicity. It increases mortality from respiratory and cardiovascular diseases. It reduces the population's life expectancy from several months to a few years [1–6].

A study that analyzed data between 1990 and 2015 determined that long-term exposure to $PM_{2.5}$ caused around 4.2 million deaths and 103.1 million disability-adjusted life years (DALYs) in 2015. Ambient particulate matter (PM) ranked fifth among the world-leading mortality risks in that year [7,8]. The World Health Organization defines a DALY as the loss of the equivalent of one year of total health. It is the sum of the years of life lost due to premature mortality (YLLs) and the years lived with a disability (YLDs) due to prevalent cases of the disease or health condition in a population. Fig. 1 shows a graphical explanation of the DALY of a given person.

Particle size is probably the most crucial parameter for describing the behavior of aerosols. Many physical laws governing their behavior depend on their size [9].

The particle size distributions of indoor and outdoor aerosols span over several orders of magnitude [9,10]. For an easier description and following the currently used instrumentation, the quantity of particles in outdoor air is provided as a mass concentration or as particulate matter concentration, i.e., as a PM_X value. The rigorous definition of PM_X is complex because it is also related to the sampling and measurement methods. Hence, most institutions and public authorities simply defined it as the fraction of particulate matter with aerodynamic particle size smaller or equal to "X" expressed in micrometers (e.g., $PM_{2.5}$) [11].

Abbreviations: UFP, Ultrafine particles; DALYs, Disability-adjusted life years; PM, Particulate matter; YLLs, Years of life lost due to premature mortality; YLDs, Years lived with a disability; ABS, Acrylonitrile butadiene styrene; FDM, Fused deposition modeling.

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https://doi.org/10.1016/j.buildenv.2022.108992
Received 24 December 2021; Received in revised form 14 March 2022; Accepted 15 March 2022
Available online 19 March 2022

The term "equivalent diameter" describes the size of particles of unknown composition and/or shape as spheres of specified density. Ultrafine particles (UFP), also called $PM_{0.1}$, are particles with an equivalent diameter (i.e., geometric, aerodynamic, mobility) smaller than 100 nm [12,13]. During the last 30 years, $PM_{2.5}$ and PM_{10} were the most used parameters to assess human exposure to particulate matter [14]. Those fractions contain particles with equivalent diameters smaller than 2.5 μm and 10 μm, respectively. Either $PM_{2.5}$ or PM_{10} also includes the fraction below 100 nm (i.e., ultrafine particles).

We conducted a scientific literature review to summarize the health effects, generation, and measurement of ultrafine particles in indoor environments. We compare such characteristics with the ones of larger fractions of PM. The study focuses on the UFP generated by daily activities indoors. We analyze the possibility of using an innovative, low-cost method to address current problems about UFP measurements reliably.

2. Ultrafine particles peculiarities

The generation of atmospheric ultrafine particles is a multi-component process. It usually involves sulfuric acid and may or may not involve ions [15]. Such particles can be created by the so-called new particle formation (NPF) process [15,16]. This process entails the formation of molecular clusters and their subsequent growth to larger sizes [17]. Understanding the earliest stages of atmospheric aerosol production necessitates a thorough understanding of neutral and charged cluster densities, chemical composition, and the gaseous components involved in their creation and development [18].

The first step is the nucleation of stable nuclei, which are too small (<2 nm) and therefore very difficult to be detected with current instrumentation. Then, gaseous components (e.g., volatile organic compounds and semivolatile organic compounds, VOC and SVOC, respectively) contribute either to the formation of new nuclei (homogeneous condensation) or condensate toward existing nuclei (heterogeneous condensation) [15,16].

Subsequently, the coagulation process takes place. We can define it as the collision of two particles that results in the production of a single particle. Freshly created ultrafine particles rapidly coagulate when they contact other particles [19]. In the case of solid particles, the coagulation process is usually called agglomeration, and the resulting particle clusters are known as agglomerates [9].

As a result, coagulation and agglomeration are critical steps in the deposition of UFP because their net result is a continuous decrease in particle number concentration combined with an increase in particle size [9]. The UFP number concentration decreases very sharply away from the emission source due to the rapid coagulation of the particles [16]. However, coagulation has little impact on PM mass concentrations [16].

Exposure to PM has been linked with several diseases. Lung function changes, airway inflammation, increased allergy reactions, vascular thrombogenic effects, altered endothelial function, altered heart rate, accelerated atherosclerosis, and increased brain inflammation have all been observed in some studies. These findings are consistent with ultrafine or fine particle exposure, except for brain diseases that are mostly correlated to the UFP [2,20–24].

The approach used for $PM_{2.5}$ cannot be applied to the measurement and assessment of the effects of ultrafine particles on human health for several reasons, here listed below.

Most studies about the PM exposure effect assume particles are spread homogeneously in the area considered and that temporal variations are negligible [2,8,25–29]. However, $PM_{0.1}$ is highly variable in space and time and this assumption is invalid [30–33].

Values of $PM_{2.5}$ and PM_{10} are mass concentrations (i.e., the mass of particles in a given air volume). Instead, UFP concentration is the particle number concentration (i.e., count of particles in a given air volume) because its mass concentration is too low to be measurable reliably and effectively. UFP marginally contributes to indoor and outdoor aerosols' overall particle mass concentration. For instance, UFP concentration is around 7% of $PM_{2.5}$ mass in a typical urban atmosphere. However, the ultrafine fraction is the dominant contributor to the total particle count (UFP represents 95% of total particles in a typical urban atmosphere) [9,10,34]. Furthermore, some studies found that the correlation coefficient between UFP and $PM_{2.5}$ measurements is between −0.18 and 0.11 [35,36], which is a weak statistical correlation between them [37].

The smaller the particles, the more toxic they can be for human health because the surface-to-volume ratio is inversely proportional to their size. Consequently, for a given dose, the surface of smaller particles potentially represents a much more extensive interface to transmit toxic chemicals than in the case of larger particles [2].

For example, we can analyze a monodisperse aerosol (i.e., an aerosol with particles of one size) with spherical bulk particles with a density of 1000 kg/m^3 and a $PM_{2.5}$ mass concentration of 10 $\mu m/m^3$. If such an aerosol is made of 2.5 μm particles, the particle number concentration is 1.22 $\#/cm^3$, and the particle surface concentration is 0.27 m^2/g. On the other hand, if such an aerosol is made of 20 nm particles, the particle number concentration is 2.39×10^6 $\#/cm^3$, and the particle surface concentration is 33.33 m^2/g. Therefore, for the same mass of aerosol, the 20 nm-size aerosol has an interface 123 times larger than the one of the 2.5 μm-size aerosol. Oberdörster [38] confirmed this finding in his study. He exposed rats to either fine (≈250 nm) or ultrafine (≈20 nm) to different doses ranging from 30 to 2000 μg. He found that ultrafine particles elicited a significantly greater inflammatory cell response for the same dose than larger particles. Furthermore, he found a direct correlation between the inflammatory cell response and the surface of the inhaled particles. Therefore, he concluded that particle surface is the most appropriate dosimetric rather than the mass of those particles to assess the health effects of PM exposure.

Deposition patterns and clearance mechanisms in the respiratory system are very different from UFP and larger PM fractions. In fact, in the size range between 1 and 100 nm, the deposition fraction in the lungs increases as particle size decreases. Furthermore, clearance of UFP is a long process that takes several months to be completed [39,40].

After entering the respiratory system, UFP potentially translocate to the heart, liver, and brain only a few minutes after being inhaled [41]. Instead, larger particles are usually detected only in lung tissue and less likely in the blood [42]. Maher et al. [43] concluded that UFP could

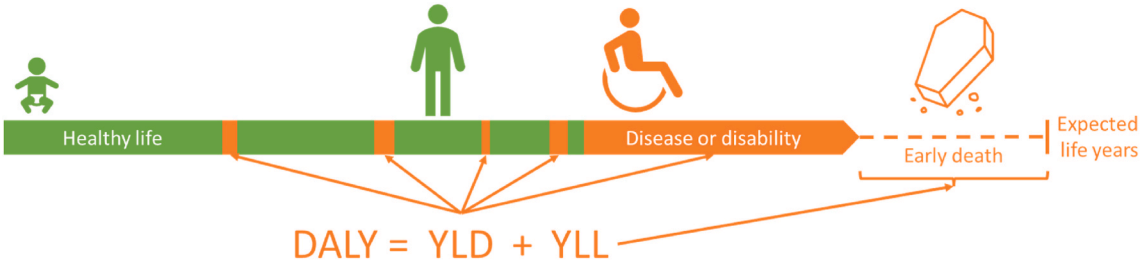

Fig. 1. Graphical explanation of disability-adjusted life years (DALYs).

reach the brain entering directly via the olfactory bulb. Bräuner et al. [44] found a direct correlation between exposure to the ultrafine fraction and permanent damage to DNA because the cells are subject to systemic oxidative stress. For toxicology assessments, scientists use biomarkers to determine whether an organism is physiologically healthy in a given environment [45]. A biomarker is "a biological response to a chemical or chemicals that gives a measure of exposure and sometimes, also a toxic effect" [46]. Biomarkers of $PM_{2.5}$ show a different lag pattern than biomarkers of UFP [35], i.e., these two fractions affect the human body independently without a fixed rule. Furthermore, Gong et al. concluded that exposure to $PM_{2.5}$ accounts predominantly for respiratory diseases while exposure to UFP accounts predominantly for cardiovascular ones.

It is not clear whether laws and regulations that set limits for $PM_{2.5}$ and PM_{10} effectively keep the UFP fraction under control [47]. Therefore, a low level of $PM_{2.5}$ or PM_{10} does not imply a low level of $PM_{0.1}$. Harrison et al. [48] concluded that using only mass parameters may underestimate the health consequences of PM exposure. They suggest considering both $PM_{0.1}$ and larger fractions of PM to assess human exposure properly.

3. Outdoor vs. Indoor human exposure to the ultrafine fraction

People living in developed countries spend between 80% and 90% of their time in indoor microenvironments [49–51], which means that indoor particulate matter is predominant in determining the exposure of humans to PM.

Combustion is the most significant anthropogenic source of $PM_{0.1}$. This source includes vehicles, industrial plants, and almost any machine using fossil fuels or biomass. Motor vehicles emissions, including non-exhaust ones, constitute the main source of UFP in urban environments [52].

Indoor aerosols are a mixture of outdoor aerosols (which penetrates buildings with a specific size-resolved efficiency) and particles generated indoors by daily human activities [53].

When indoor particle generation is low (e.g., at night, in microenvironments with limited human activities, and no combustion activities), indoor particles depend strongly on the transportation dynamics and fate of outdoor ones. Some researchers [54–58] concluded that the indoor-to-outdoor particle size distribution ratio is consistently below 1 in such conditions, either for ultrafine or larger PM fractions. Lower infiltration values were found either for ultrafine (0.41–0.70) or coarse particles (0,15–0,30) than for fine ones (0,24–0,78) [58,59]. In the case of the ultrafine fraction, we can explain that behavior either by the removal efficiency of the buildings' HVAC system or by the deposition by Brownian diffusion. For coarse particles, such behavior is explained by the gravitational settling [59–61]. Long et al. [59] compares deposition rates (both theoretical and experimental) in their study, concluding that indoor particle deposition depends on particle size and other site-specific conditions. Therefore, when indoor particle generation is low, human exposure to PM could be predicted by knowing the outdoor aerosol and the building ventilation characteristics.

On the other hand, in buildings with a high indoor particle generation (e.g., restaurants), the average indoor to outdoor $PM_{0.1}$ ratio could be around 5, with peaks reaching ratio values of 14 [56]. This behavior is typical for poorly ventilated homes [59].

Almost any type of indoor activity produces a considerable amount of UFP. Several studies [56,57,62,63] concluded that combustion, electric heating, and cleaning are the main generators of UFP. They also demonstrated that indoor particle events are intermittent and highly variable, requiring the uninterrupted use of instrumentation for their characterization.

Therefore, in buildings with a significant generation of indoor UFP, the particle size distribution and composition indoors are very different from outdoors. UFP generated indoors account for 50%–80% of the total indoor UFP [64].

Most air pollution epidemiology studies did not account for the exposure to UFP in indoor microenvironments [53]. Therefore, at the moment, it is not clear the recommended exposure level for the ultrafine fraction in indoor environments. Moreover, current outdoor air quality standards do not include a specific requirement for UFP and, consequently, do not provide any support for assessing the health effects of UFP in indoor environments.

4. Indoor generation of ultrafine particles

In residential and commercial buildings, almost any activity is a potential source of $PM_{0.1}$. Several studies analyzed the UFP generation of everyday activities like cooking, smoking, burning candles, cleaning, using a spray, ironing, electric heating, cleaning with a vacuum, digital and 3D printing [56,57,62,63].

When assessing the generation of UFP associated with a given event, besides the particle number concentration, it is necessary to evaluate the time needed to reach the highest particle concentration and the time needed to return to the background particle concentration again. Those parameters are essential for understanding the behavior of particles generated by the event and assessing the dose correlated with such exposure to UFP.

Afshari et al. [65] found that sources of $PM_{0.1}$ generate particles with a time required for reaching the particle concentration peak from just a few seconds to a few minutes. Such values represent a very high particle generation rate, with an order of magnitude in the range 10^{10}-10^{12} #/min.

On the other hand, the time required for reaching the initial background particle concentration again is much longer, varying from a few tens of minutes to a few hours [65]. The concentration decay follows an exponential law [63]. Furthermore, He et al. [66] found that the lower the ventilation rate, the longer the particle decay time, as expected. Particles generated by smoking seem to have the longest decay time, with values of several hours [67].

To define a baseline for the background concentration, different studies measured an average particle number concentration of 7.58×10^3 #/cm^3, with values ranging between 1.50×10^3 #/cm^3 and 14.60×10^3 #/cm^3 [57,62,67].

Among the UFP indoor sources mentioned, turning on a clean iron without steam is the lowest particle generator, with a particle generation rate of 7.00×10^8 #/min [65].

Cooking and combustion activities (e.g., cooking in an electric stove or oven, smoking, burning a candle, or a match) are the highest UFP generators. Such activities have a particle generation rate of 2.02×10^{12} #/min, in the range between 7.86×10^{12} #/min and 5.25×10^{13} #/min [57,62,63,65–67]. Non-combustion sources with heated surfaces (e.g., electric radiators, fan heaters, and hair dryers) are comparable to combustion sources if dust is present on their surfaces. These sources have an UFP generation rate of 2.75×10^{11} #/min, in the range between 7.00×10^8 #/min and 8.84×10^{11} #/min [62,65–67].

Particular attention shall be paid when cooking activities occur, either at home or for professional activities in restaurants. Such activities produce a very high amount of UFP, with a generation rate of 2.16×10^{12} #/min, in the range between 1.27×10^{11} #/min and 7.86×10^{12} #/min [57,62,63,65–67]. Furthermore, it takes between 4 and 6 h to return to the initial background concentration [67]. Zhang et al. [68] found that people are exposed to very high levels of UFP during cooking time, with concentrations up to 550 times higher than background levels. Metayer et al. and Ko et al. [69,70] conducted a study on non-smoking women in Asia. They found a direct correlation between lung cancer and cooking activities producing oil fumes in kitchens not equipped with a fume extractor. They also found that the higher the total years cooking, the higher the risk of developing lung cancer.

In the case of office activities, standard office printers have a particle generation rate up to 1.38×10^{12} #/min [63,71]. 3D printers can generate particles at a rate of 2.00×10^{11} #/min when printing

Acrylonitrile butadiene styrene (ABS) in a *Fused Deposition Modeling* (FDM) 3D printer [72].

Fig. 2 compares the particle generation rate of some daily activities. The values are presented in log-scale to show the considerable difference in particle generation by different sources.

Since many activities produce UFP at high concentrations, future studies on exposure and its health effect should follow a broader approach. Studying only emissions caused by traffic or other outdoor sources leaves unaddressed a critical portion of health impact [62].

5. Proper assessment of exposure to UFP

Usually, exposure to UFP is quantified using the particle number concentration to estimate the surface area of particles [38]. This procedure aims to estimate the exposure dose and surface interface in which the potential harmful contaminant interacts with the body. However, current standardized test methods [12] recognize that proper exposure assessment to UFP is unclear.

Since UFP are very small, accurate instruments used to measure particle concentration in that size range rely on very sophisticated technology and are usually very expensive. The typical setup to measure UFP is an arrangement of a charge neutralizer, a differential electrical mobility classifier (DEMC), with a condensation particle counter (CPC) [9,73,74]. A unique instrument that combines a charge neutralizer, a DEMC, and a CPC is a scanning differential mobility analyzing system (scanning DMAS) or mobility particle sizer spectrometer (MPSS) [75].

The aerosol neutralizer brings the particles to a known charge equilibrium. The knowledge of the charge distribution is essential to correctly measure the electrical particle mobility distribution (in other words, to correlate the particle electrical mobility with the actual particle size). Such a component produces high amounts of positive and negative ions (around 10^7 ions/cm^3), either by electrical or radioactive means [73].

The DEMC classifies the particles in a very narrow size range to obtain a quasi-monodisperse aerosol at the outlet. It sizes the particles according to their electrical mobility particle size [9]. Wiedensohler et al. and Intra et al. [73,74] described the operation of this instrument in details. A full particle size distribution can be built up by exponentially changing (i.e., scanning) the electrical field between the walls.

The smaller the particle size and the higher the charges number, the higher the electrical particle mobility. The instrument manufacturers develop a custom inversion routine algorithm to transform the measured electrical particle mobility distribution into the particle number size distribution. This algorithm uses the particle charge distribution and the DEMC transfer function to perform such transformation. Frequently, those routines are trade secrets and, therefore, not accessible [73].

After classifying the particles with a DEMC, a CPC grows and counts the particles. The aerosol passes through a supersaturated atmosphere (either of water or alcohol) in which the particles to be counted are the nuclei. Thanks to the growth process, particles can reach about 10 μm (regardless of their initial size), and an optical sensor can easily count them. Since each initial particle grows to a single droplet, the total particle number concentration of the measured aerosol remains the same [9].

Instruments on the market for measuring UFP number concentration can be very different from each other. The most critical parameters are the lowest size cut (i.e., smallest particle size detectable by instrument) and the detection efficiency in each size range because the instrument detects just a fraction of the aerosol particles [9]. Those two parameters are related to each other.

The detection efficiency curve of a specific instrument, also known as its counting efficiency curve, provides the counting efficiency for each particle size interval within its measuring range [76]. The detection efficiency becomes zero for particles smaller than a specific size. Then the detection efficiency increases steeply till reaching almost 100% for particles larger than another specific size. The curve shape is similar to the collection efficiency curve of inertial impactors. Usually, manufacturers define the lowest size cut as the size in which the detection efficiency is 50% (d_{50}). Therefore, the lowest size cut strongly affects the absolute particle number concentration provided by the instrument when measuring a given aerosol.

To obtain a correct absolute particle number concentration,

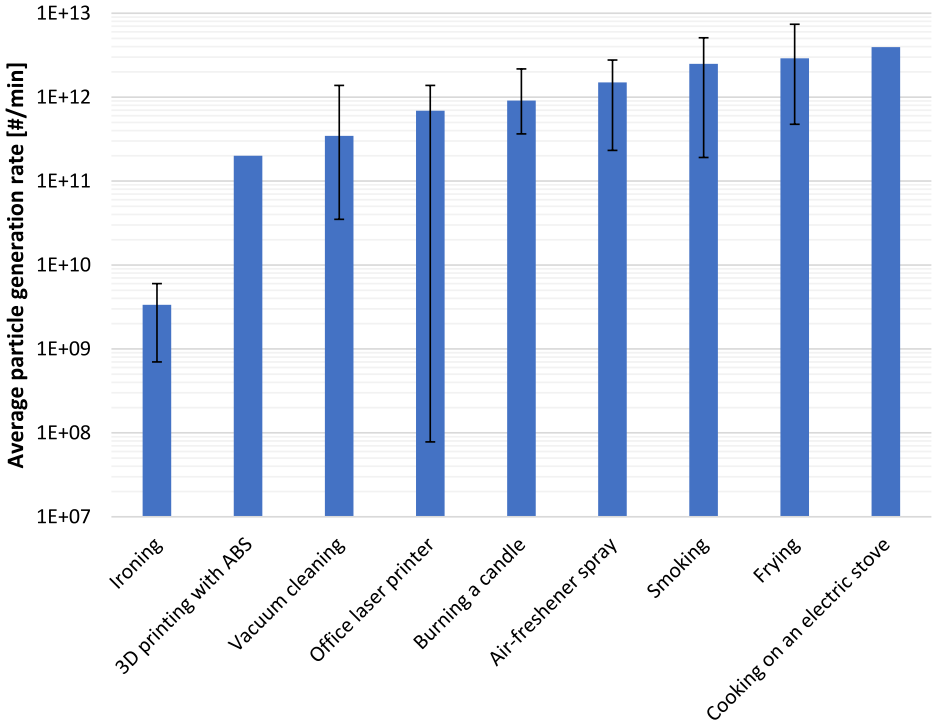

Fig. 2. Average particle number concentration produced by different activities [57,62,63,65,66,71,72].

manufacturers adjust the particle number concentration supplied by the instrument using its curve of detection efficiency. However, such corrections, together with other uncertainties sources (e.g., DEMC transfer function, particle losses along with the instrument, differences in the neutralizer charge distribution, instability in the sheath flow rate), can lead to substantial errors, either in terms of particle size distribution or particle number concentration [77]. For instance, a 1% error in the sheath airflow corresponds to a 10% error in the total particle number concentration (assuming a ratio of 10:1 of the sheath and sampling flow) [73].

Imhof et al. [78] compared the total particle number concentrations provided by three scanning DMASs of the same brand and model. They found a measurements discrepancy of 30% and 25% in the size range <50 nm and 60–120 nm, respectively. Furthermore, they were unable to identify the reasons for these discrepancies.

Here below is an example of the effect of the lower detection limit on the measurement of the total particle number concentration.

Fig. 3. a shows a typical urban aerosol size distribution on a log-log scale. The solid, slightly transparent line represents the combined particle size distribution. The dashed lines represent the individual modes expressed in particle number concentration. This chart shows the huge difference (i.e., several orders of magnitude) of the particle number concentration as a function of particle size.

Fig. 3. b shows the same data as Fig. 3. a but on a linear-log scale. This representation clarifies that the coarse mode contributes only marginally to the particle count. Furthermore, most particles (>95%) are ultrafine.

Another source of uncertainty is the response time of the sampling instruments. Coagulation strongly affects UFP size distribution and concentration. Therefore, such properties depend on the time elapsed between particle generation and sampling. A faster-response version of scanning DMAS can provide much higher frequency measurements by sacrificing size resolution. Therefore, such instruments can measure UFP properties immediately after their generation and consequently before being affected by the coagulation process. Those faster-response instruments are typically used to characterize diesel exhaust emissions. Asbach et al. [79] compared the results of scanning DMASs and their faster-response version when measuring an aerosol in a wind tunnel. In their study, the faster-response instrument version sized smaller particles than the "normal" scanning DMASs, precisely a count median diameter between 9% and 22% smaller.

Even assuming that all the above uncertainty sources could be neglectable, instruments with different lowest detection limits provide very different total particle number concentration values. Therefore, particle number concentrations provided by different studies are not comparable.

Let us analyze which fraction would be neglected by instruments with different lowest detection limits. We consider the following lowest detection sizes: 2.5 nm, 5 nm, 7 nm, 10 nm, and 20 nm, selected from instruments available on the market (TSI 3788, GRIMM 5416, TSI 3783, TSI 3007, and TSI 8525, respectively – TSI Incorporated, Shoreview, MN, USA, and GRIMM Aerosol Technik GmbH & Co., Ainring, Germany). Using those data, the errors measuring the total particle number concentration are: 0.12%, 2.68%, 9.43%, 23.59%, and 58.53%, respectively. As an example, for a total particle number concentration of 138,000 #/cm^3, those instruments will provide measurement results between 57,229 #/cm^3 and 137,834 #/cm^3. Fig. 3. b shows a graphical representation of those size-cut points in the case of a typical urban aerosol. The instruments considered in this example neglect the portion of the count distribution on the left of the dashed lines.

In the case of indoor particles emitted when cooking, Fortmann et al. [80,81] found that most particles are smaller than 40 nm. Therefore, in

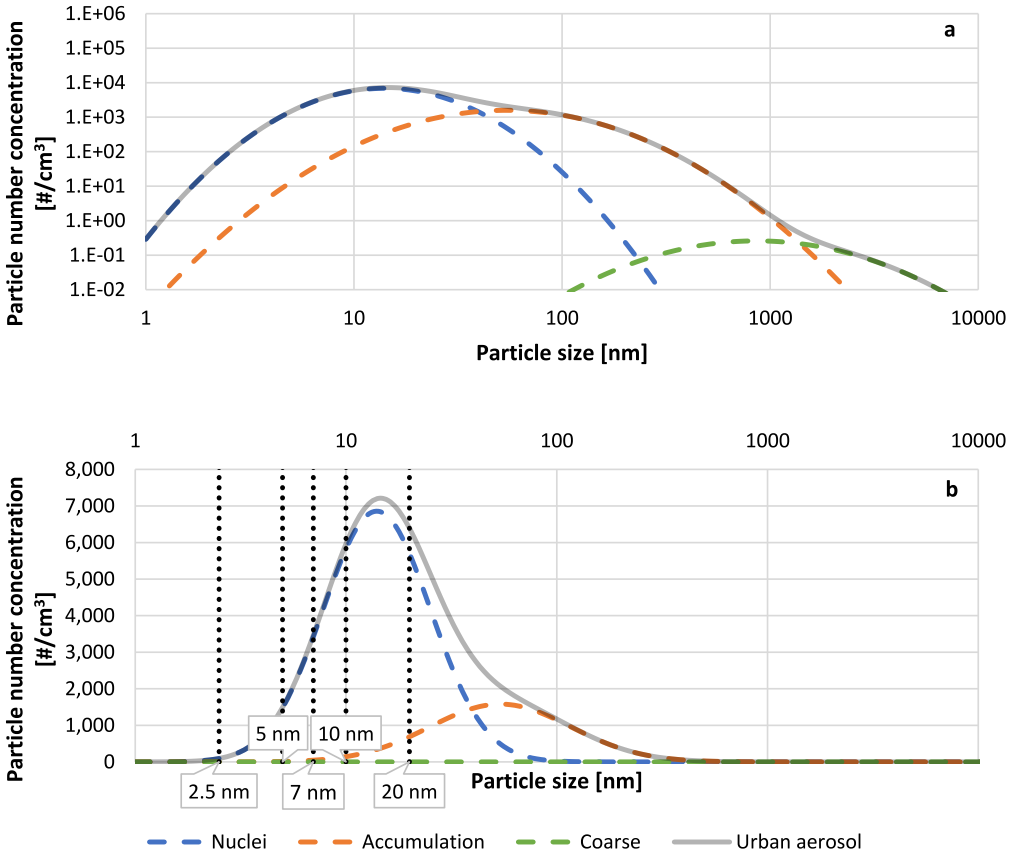

Fig. 3. Urban aerosol particle number size distribution with nuclei, accumulation, and coarse mode [9]. Fig. 3. a is in a log-log scale. Fig. 3. b is in a linear-log scale.

this case, the lowest detection limit of instruments is even more critical than the typical urban aerosol discussed above. For example, Géhin et al. [50] measured higher total particle number concentrations than others because they used instruments with lower detection limits.

Since the ultrafine particle concentration is non-homogeneous in space and very time-dependent, personal sampling devices are the best option to assess human exposure. In this way, it is possible to take into account local peaks of UFP that non-mobile sampling devices may not capture. However, the cost of ultrafine portable monitors is between 5,000 EUR and 10,000 EUR [82], which is relatively expensive. Therefore, these monitors are unlikely to be used widely since each person shall carry one.

Several studies evaluated the possibility to estimate UFP number concentration using the instrumentation already operated by environmental authorities. They found a reasonably good statistical correlation (R^2 from 0.56 to 0.90) between nitrogen oxides concentration (NO_X) in ambient air and UFP concentration [83–85]. However, Kwasny et al. [83] specify that this approach can be used only to estimate the trend of particle number concentration but cannot provide a fully reliable tool to replace $PM_{0.1}$ monitoring. Accordingly, low-cost NO_X sensors are good candidates for creating a dense, accurate monitoring network of UFP, including indoor environments [84,86]. This approach could be helpful to estimate the overall ultrafine particle concentration, but it cannot provide information about the particle size distribution.

Mead et al. [87] evaluated the possibility of creating a dense gas sensor network for monitoring CO, NO, and NO_2, temperature, and relative humidity. They developed two low-cost (<100 GBP) sensors (one mobile and another static) integrated with a GPS for positioning and a GPRS for data communication (for real-time data). They could operate such a network with 40 nodes over 12 months and estimate a lifetime of several years. The NO and NO_2 data measured with these sensors statistically correlated very well (R^2 from 0.80 to 0.95 and 0.89 to 0.92, respectively) with reference instruments. Furthermore, their results quantified personal exposure as a function of transportation type and urban air quality.

6. Conclusion

Regardless of particle size, exposure to PM can produce several diseases, including cardiovascular and respiratory morbidity and death. Current air quality guidelines provide limits only for larger fractions of PM (i.e., $PM_{2.5}$ and PM_{10}). However, several studies show that the UFP fraction impacts the human body differently from larger fractions. Hence, it is necessary to perform human exposure assessments to UFP separately. Furthermore, there is no evidence that current efforts to reduce $PM_{2.5}$ or PM_{10} also reduce UFP concentration.

$PM_{0.1}$ is highly variable in both space and time. Therefore, to assess UFP variability in a large area, it is not recommended to use local measurements of larger fractions of PM. In conclusion, the most recent studies regarding UFP health effects are still insufficient and inconclusive because current $PM_{0.1}$ data is not measured reliably and extensively. Using ultrafine portable monitors on the market would allow determining properly human exposure to $PM_{0.1}$, but such instruments are relatively expensive for wide use.

Since people spend most of their time indoors, indoor aerosols are the major contributor to human exposure to PM. In cases where no combustion activities occur, indoor particle concentration is generally lower than outdoor. Outdoor aerosol data and the building ventilation system characteristics allow the calculation of indoor particle concentration. Instead, indoor aerosol concentration can be several times higher than outdoors in environments with high indoor particle generation. In this case, outdoor air quality alone does not predict indoor concentration.

As in the case of other contaminants, the following approaches are valid also for the control of UFP to improve indoor air quality:

1) Identification, removal, or reduction of indoor UFP sources;
2) Extraction of UFP as close as possible to the source;
3) Filtration of indoor air, either with centralized devices (e.g., ventilation systems) or localized ones (room air cleaners).

Indoor UFP generators can produce particles at a 10^{12} #/min rate, causing the particle concentration to rise in a few seconds up to a few minutes. On the other hand, returning to particle concentration background level takes tens of minutes to a few hours. Combustion activities indoors are the highest generator of UFP. Therefore, studies based only on outdoor data leave a significant portion of human exposure unaddressed.

Standardized measurement procedures are needed to assess UFP concentration properly. Such standards shall prescribe the smallest size for the detection limit of measuring instruments to compare absolute UFP concentration among different studies consistently.

There is a good correlation between UFP and NO_X concentrations in ambient air. Hence, low-cost NO_X sensors are good candidates to estimate spatially and temporally UFP concentrations, which is currently not feasible using more sophisticated scientific instrumentation (e.g., scanning DMAS). Preliminary studies demonstrated the potential of a dense, low-cost network for monitoring pollution at ambient levels. This approach is suitable both outdoors and indoors.

Future studies should focus on developing routine methods for ultrafine particle concentration measurement. This approach would provide a broader understanding of UFP and possibly the development of regulations for UFP exposure assessments. Furthermore, we suggest studying active air cleaners (e.g., ionizers or UV lamps) in indoor environments. Some devices could potentially generate UFP.

CRediT authorship contribution statement

Jesus Marval: Conceptualization, Investigation, Writing – original draft. **Paolo Tronville:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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