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Review on Sampling Methods and Health Impacts of Fine ($PM_{2.5}$, $\leq$2.5 µm) and Ultrafine (UFP, $PM_{0.1}$, $\leq$0.1 µm) Particles

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Abstract: Airborne particulate matter (PM) is of great concern in the modern-day atmosphere owing to its association with a variety of health impacts, such as respiratory and cardiovascular diseases. Of the various size fractions of PM, it is the finer fractions that are most harmful to health, in particular ultrafine particles ($PM_{0.1}$; UFPs), with an aerodynamic diameter $\leq$ 100 nm. The smaller size fractions, of $\leq$2.5 µm ($PM_{2.5}$; fine particles) and $\leq$0.1 µm ($PM_{0.1}$; ultrafine particles), have been shown to have numerous linkages to negative health effects; however, their collection/sampling remains challenging. This review paper employed a comprehensive literature review methodology; 200 studies were evaluated based on the rigor of their methodologies, including the validity of experimental designs, data collection methods, and statistical analyses. Studies with robust methodologies were prioritised for inclusion. This review paper critically assesses the health risks associated with fine and ultrafine particles, highlighting vehicular emissions as the most significant source of particulate-related health effects. While coal combustion, diesel exhaust, household wood combustors' emissions, and Earth's crust dust also pose health risks, evidence suggests that exposure to particulates from vehicular emissions has the greatest impact on human health due to their widespread distribution and contribution to air pollution-related diseases. This article comprehensively examines current sampling technologies, specifically focusing on the collection and sampling of ultrafine particles (UFP) from ambient air to facilitate toxicological and physiochemical characterisation efforts. This article discusses diverse approaches to collect fine and ultrafine particulates, along with experimental endeavours to assess ultrafine particle concentrations across various microenvironments. Following meticulous evaluation of sampling techniques, high-volume air samplers such as the Chem Vol Model 2400 High Volume Cascade Impactor and low-volume samplers like the Personal Cascade Impactor Sampler (PCIS) emerge as effective methods. These techniques offer advantages in particle size fractionation, collection efficiency, and adaptability to different sampling environments, positioning them as valuable tools for precise characterisation of particulate matter in air quality research and environmental monitoring.

Keywords: $PM_{2.5}$; $PM_{0.1}$; collection; technologies; instruments; health

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1. Introduction

Ultrafine particles, characterised by their extremely small size, with diameters typically less than 0.1 µm, are ubiquitous in the atmosphere and originate from a multitude of natural and anthropogenic sources. Natural sources include emissions from volcanic eruptions, forest fires, sea spray, and biological processes such as pollen release and fungal spores [1]. Researchers have stratified PM into primary particles [2–4] and secondary particles [3–5]. Primary particles, characterised by diameters $\leq$ 2.5 µm and diameters $\leq$ 0.1 µm, emanate predominantly from combustion processes and are swiftly introduced into the atmosphere. In contrast, secondary particles, featuring diameters $\geq$ 2.5 µm and diameters $\leq$ 10 µm, encompass particles derived from diverse sources and agglomerations of various particulate constituents. According to size and type, PM is divided into categories such as particulate contaminants, biological contaminants, types of dust and gases, as shown in Table 1. Anthropogenic activities contribute significantly to UFP emissions through combustion processes from vehicles, industrial activities, power plants, and residential heating [6]. Additionally, UFPs can form through chemical reactions in the atmosphere, such as the transformation of gaseous pollutants like sulphur dioxide and nitrogen oxides into particulate matter [7].

Table 1. Categories of PM based on types and sizes [8].

Type		PM Diameter (µm)
Particulate contaminants	Soot	0.01–0.8
	Smog	0.01–1
	Tobacco smoke	0.01–1
	Fly ash	1–100
	Cement dust	8–100
Biological contaminants	Viruses	0.01–1
	Bacteria and bacterial spores	0.7–10
	Fungi and moulds	2–12
	Allergens (dogs, cats, pollen, household dust)	0.1–100
Types of dust	Atmospheric dust	0.01–1
	Settling dust	1–100
	Heavy dust	100–1000
Gases	Different gaseous contaminants	0.0001–0.01

The measurement of ambient UFP levels poses challenges both spatially and temporally due to their steep decline in concentration with distance from emission sources. Additionally, UFPs undergo size enlargement from nucleation to accumulation modes via coagulation and condensation processes. In the European Union (EU), total UFP emissions in 2008 were estimated at 271 kilotons, originating from various sectors including agricultural sources (8%), power generation (4%), commercial and residential activities (15%), industrial processes (5%), industrial combustion (12%), road transport (34%), miscellaneous transportation and machinery (22%) [9]. Predominantly, in urban environments, on-road vehicles function as the principal source of UFP emissions. Studies on source apportionment conducted in urban areas such as London demonstrate that the highest contribution to ambient particle number concentrations (PNC) comes from vehicle exhaust emissions (65%), with urban background sources contributing (18%), along with contributions from resuspension (5%), particles that are produced when brake pads and rotors wear down during braking in vehicles (also called as brake dust) (2%), and other unspecified sources (10%) [10]. Exposures to UFPs in occupational settings are notably higher in environments where there are combustion processes, fast-paced manufacturing activities, and tasks involving elevated temperatures such as welding and smelting [11]. In the United States, predictions were made regarding the concentrations of UFP mass in regions across 39 cities during episodes of summertime air pollution, using data from the national emission inventory provided by the US Environmental Protection Agency. The primary source of UFPs in major cities was found to be non-residential natural gas combustion, while on-road gasoline and diesel vehicles contributed an average of 14% to the total regional UFP emissions, although this figure may have been underestimated due to limitations in measurement methods [12]. The limitations in measurement methods could stem from several factors inherent in monitoring UFP emissions from on road vehicles. Firstly, existing measurement techniques may not capture the full spectrum of UFP emissions, particularly those associated with highly localised and transient peaks near roadways. Venecek et al. (2019)'s study's resolution, constrained by 4 km grid cells, might have led to the inability to resolve peak contributions within 0.3 km of roadways, where UFP concentrations are expected to be highest [12].

Their minuscule size grants UFPs unique physical and chemical properties, allowing them to remain suspended in the air for extended periods and facilitating their penetration deep into the respiratory system upon inhalation. Owing to their small size, UFPs are considered hazardous to human health, as they can penetrate deeply into the lungs and undergo systemic translocation to various organs and tissues [13,14], including the bloodstream [15,16], heart [17], brain [18,19], liver [20], kidneys [21], and reproductive organs [22]. Numerous studies have explored the associations between airborne particulate matter (PM) and health, with a significant focus on cardiovascular [20,23–26] and respiratory diseases [27–31], while also examining other health outcomes such as neurological disorders [32,33], immune system dysfunction [34,35], reproductive health impacts [36,37], and systemic inflammation [38,39]. A significant amount of effort has also been invested in epidemiological work, for instance investigating hospitalisations owing to respiratory problems caused by PM [40–43]. There are several review studies underwent to study the UFPs, their health effects and measurement methods. Viitanen et al. (2017) stated workers' exposure to UFP in industries like welding and metalwork can surpass typical urban concentrations by over 100 fold [44]. However, despite these alarming findings, measurements of UFP in work environments remain limited and heterogeneous, hindering the ability to draw comprehensive conclusions. Harmonising measurement strategies is crucial for generating reliable and comparable data in the future.

The respiratory health effects of UFPs on children, though potentially more toxic than larger particulate matter like $PM_{2.5}$, remain poorly understood. Heinzerling et al. (2016) conducted a review of 12 relevant articles and found associations between UFP exposure and respiratory issues such as wheezing, asthma, and decreased lung function in children [45]. However, due to heterogeneity in study designs and definitions, along with inconclusive results from multivariate models, the relationship between UFPs and children's respiratory health remains uncertain. Oliveira et al. (2019) conducted a comprehensive review to explore the impact of UFPs on children's health, finding a significant association between UFP exposure and adverse health outcomes, particularly in children with respiratory diseases [46]. The review highlighted that UFPs can penetrate various bodily systems due to their small size, leading to alterations in inflammatory biomarkers and declining lung function in affected children. Ali et al. (2022) conducted a comprehensive review outlining the sources, properties, exposure routes, toxicity mechanisms, and health impacts of UFPs, emphasising inhalation as the primary exposure route leading to various adverse health outcomes [47]. They underscored the urgent need for air quality guidelines and proposed future research to investigate the relationship between UFP physicochemical properties and health symptoms, focusing on chemical transformations in the body, biological behaviour, and toxicological effects.

Abdillah et al. (2022) conducted a review highlighting that ambient ultrafine particles UFPs originate from various sources and carry toxic compounds such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) [48]. They propose measurement methods including stationary and mobile approaches for environmental profiling, as well as the use of low-cost sensors for UFP monitoring. Additionally, the study underscores the associations between short-term UFP exposure and cardiopulmonary effects, as well as the long-term associations with chronic conditions like chronic obstructive pulmonary disease (COPD), cardiovascular disease (CVD), and pre-term birth, suggesting the need for further epidemiological investigations. There are studies related to measurement methods of fine and ultrafine particles, discussed thoroughly in Part II of this review paper. Impactors and aerodynamic lenses are utilised to isolate UFP fractions for chemical analysis, often employing cascade impactors like MOUDI. These methods require sufficient sampling flow rates and homogeneous deposits for various chemical analyses, including mass, elements, ions, and organic compounds such as polycyclic aromatic hydrocarbons (PAHs). Chow and Watson (2007) surveyed 25 ambient studies, predominantly from urban areas, revealing that organic material, including PAHs, constituted the most abundant portion of UP, often found near industrial sites, suggesting a semi-volatile composition consistent with engine oils or secondary organic aerosols [49].

In view of the small size and penetration capacity of PM and UFPs, this review aims to find the health effects of these particulates originating from anthropogenic and natural sources. Due to their lethal effect on human health, the toxicological study and characterisation of these particles is immensely needed, which requires the good collection and sampling technologies. There are particles in various size ranges as shown in Table 1, one of them is $PM_{1.0}$ which is indeed increasingly measured and recognised, the focus of this review was primarily on the other finer fractions of airborne particulate matter, specifically $PM_{2.5}$ (fine particles) and $PM_{1.0}$ (ultrafine particles or UFPs), due to their well-documented association with adverse health effects. Moreover, the decision to prioritise $PM_{2.5}$ and $PM_{1.0}$ in this review was informed by the current state of research and regulatory focus. These fractions have been extensively studied and are subject to regulatory standards worldwide, reflecting their recognised importance in air quality management and public health protection. However, it is worth noting that the exclusion of $PM_{1.0}$ does not diminish its significance or relevance in air quality research. Various instruments, however, are still being used to collect fine and UFP, and this research is different in a way that it endeavours to comprehensively enumerate almost every conceivable instrument designed for the collection of ultrafine and fine particles available to date.

2. Methodology

This review is structured into two sections (Figure 1), each addressing distinct aspects of fine and ultrafine particles. The first section (Part I) comprehensively examines the effects of fine and ultrafine particles on human health, encompassing a detailed exploration of their physiological impacts, epidemiological findings, and mechanistic pathways underlying their adverse health outcomes. In the subsequent section (Part II), a thorough analysis of sampling methodologies employed for the characterisation of fine and ultrafine particles is presented, encompassing discussions on various sampling techniques, instrumentation, and sampling strategies utilised in research and environmental monitoring endeavours. This review paper meticulously implemented a comprehensive methodology for its literature review, meticulously scrutinising a total of 200 studies.

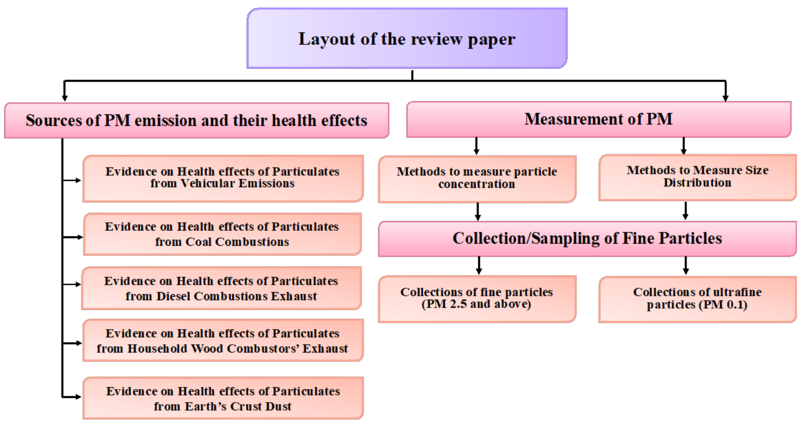

Figure 1. Structure of this review paper.

The search for relevant literature encompassed a comprehensive exploration across various scientific databases, including but not limited to PubMed, Web of Science, Science Direct, Scopus, and Google Scholar. Multiple keyword combinations were employed to ensure a thorough investigation into pertinent areas related to PM research. These combinations involved terms such as microenvironments, sampling instrument, high-volume samplers fine particulate samplers, gravimetric measurements, collection technologies, mass concentrations of PM and UFP, oxidative stress, toxicity, cell models for PM exposure, gene expressions, cytotoxicity, respiratory disorders, and lung epithelial cells. The search strategy was iterative, with modifications made to the keyword combinations based on the success rate and precision of the outcomes obtained. This iterative process involved repeated searches using Google/Google Scholar and adjustment of search term combinations to refine the scope of the investigation and maximise the relevance of the retrieved literature.

Each study underwent thorough evaluation, with a particular focus on the robustness of its methodologies. This evaluation encompassed an assessment of various facets, such as the integrity of experimental designs employed, the effectiveness of data collection methods utilised, and the soundness of statistical analyses conducted. Throughout this meticulous process, studies demonstrating robust methodologies were accorded higher priority for inclusion in this review. This approach ensured that only studies meeting stringent criteria for methodological rigor were ultimately incorporated, thereby enhancing the credibility and reliability of this review's findings. This organised review aims to provide a holistic understanding of the health implications of fine and ultrafine particles while elucidating the methodologies employed in their sampling and collection, thus contributing to advancements in both scientific knowledge and practical applications in air quality assessment and management.

3. Sources of Particulate Matter Emissions and Their Effect on Human Health

Pollutants, as identified by comprehensive pollution studies, constitute a complex mixture of gases and particulates, each possessing distinct compositions and sizes. These particulates originate from a diverse array of sources, encompassing both human activities (anthropogenic) and natural processes as shown in Figure 2. Particulate matter within the Earth's atmosphere manifests in two principal forms: primary particles and secondary particles [50].

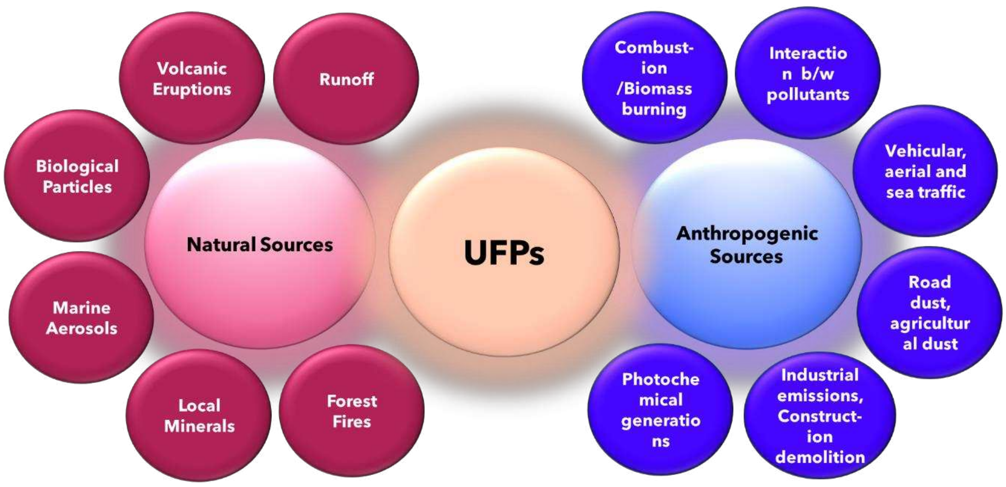

Figure 2. Sources of ultrafine particulate matter.

Primary particles originate directly from emission sources, encompassing a spectrum of chemical species expelled into the air through vehicular exhausts, industrial activities, and natural phenomena like biomass burning [51]. In contrast, secondary particles undergo formation through intricate chemical reactions occurring within the atmospheric milieu [52]. These reactions primarily involve the condensation of semi-volatile organic compounds onto existing aerosol particles. The semi-volatile compounds, characterised by their propensity for phase transitions between gas and condensed phases, undergo condensation onto existing particulates, thereby augmenting particle size and mass. Furthermore, nucleation processes contribute significantly to the generation of secondary particulate matter. Nucleation entails the spontaneous formation of molecular clusters from gaseous precursors, followed by their subsequent growth into stable aerosol particles. This mechanism serves as a vital pathway for the production of new particulates within the atmosphere, contributing to the overall abundance of secondary particulate matter over time.

The intricate interplay of chemical reactions, involving condensation and nucleation processes, governs the dynamics of particulate matter formation in the atmosphere. Understanding these chemical mechanisms is paramount for elucidating the composition, evolution, and environmental impact of atmospheric particulate matter. In densely populated regions worldwide, such as Europe, China, and the USA, road transport emerges as a significant contributor to particulate matter pollution. In these urban areas, vehicular emissions release particles and their precursors into the atmosphere, contributing substantially to the overall particulate load. Additionally, mechanical actions associated with road transport, including tire wear and braking system attrition, further exacerbate particulate emissions [53].

3.1. Health Risk Due to Fine and Ultrafine Particles

To date, research exploring the health impacts of UFPs remains relatively limited in comparison to other air pollutants. For instance, Frampton et al. (2006) conducted a notable investigation into the effects of UFP on both asthmatic and non-asthmatic individuals [54]. The study concluded that for both groups, exposure to UFPs compromised the immune system by decreasing the blood leukocytes. Due to the small particle size and quick diffusion, UFPs can reach and deposit in the alveolar area of the human lung more effectively than bigger particles if inhaled [55,56]. UFPs could pass by the lungs' alveolar macrophages and could enter into lungs' interstitial space within a tissue, as well as potentially the vascular bed [13,56]. From the lungs, they can possibly travel toward other organs via the lymphatic and blood vessels [57,58]. For example, Brauner et al. (2007) investigated the impact of vehicle exhaust derived UFPs (of diameters 12, 23, 57 and 212 nm) on human blood cells under controlled laboratory conditions, finding that 57 nm were able to cause damage to DNA via oxidative stress [59]. According to Delfino et al. (2005), UFPs emitted from vehicular sources possess the capability to induce harm to pulmonary cells [60]. This is attributed to their emission of high concentrations of reactive oxygen species (ROS), which are known to exert oxidative stress on cellular components. Additionally, UFPs are characterised by a significant cumulative surface area, which enhances their potential interactions with biological entities, including pulmonary cells.

Li et al. (2003) and Nel (2005) studied that the pro-oxidative aromatic hydrocarbon and the transition metallic elements found in UFPs are thought to contribute to the generation of ROS; Target cells, including macrophages and bronchial epithelial cells, also develop ROS as a result of biologically triggered redox mechanisms that occur inside the mitochondria in reaction to UFP absorption [61,62]. Li et al. (2003) demonstrated that UFPs from vehicular emissions, particularly in the Los Angeles basin, exhibit greater potency in inducing oxidative stress compared to fine and coarse particles [61]. This potency is attributed to the higher concentration of ROS released by UFPs, as measured by various assays including DTT (dithiothreitol), HO-1 (heme oxygenase-1), and glutathione assays. The enhanced biological potency of UFPs is directly correlated with the presence of organic carbon and polycyclic aromatic hydrocarbons (PAHs) in the particles. These organic agents contribute to the generation of redox activity, potentially exacerbating oxidative stress and cellular damage. Additionally, UFPs are implicated in inducing mitochondrial damage in pulmonary cells, potentially through the release of redox cycling chemicals. This damage may contribute to cellular apoptosis and inflammatory responses.

Moreover, many investigations related UFP exposures with variations in Heart Rate Variability [63–69]. Chan et al. (2004) investigated that in a pool involving healthy persons and elder patients in Taiwan, they observed strong inverse associations among 1 and 4 h moving mean of individual UFP exposure and SDNN (standard deviation of all normal-to-normal (NN) interval), RMSSD (root mean square of successive differences in adjacent NN interval), HF and LF (high and low frequency power) [70]. The SDNN, RMSSD, LF and HF are the typical HRV specifications showing time domain measurements taken directly from the delays between successive heartbeats. Chan et al. (2004) studied that individual UFP exposure were demonstrated to be more highly correlated with HRV in older people as compared to healthy adults, with the largest correlation found at 2 h moving averages; however, the orientations of the correlations were similar across both groups [70].

3.1.1. Evidence on Health Effects of Particulates from Vehicular Emissions

Road transport emissions are the primary contributor to $PM_{0.1}$ in urban areas [48,71–73]. Secondary particulates, come along with the emission of PM. These are generated through hot exhaust gases (which comprise CO_2, CO, hydrocarbons, and NO_x). Heo et al. (2014) used time-series assessments to investigate the effects of $PM_{2.5}$ weight as well as constituent composition along with their provenance, upon lifespan. Many chemical components, as well as the quantity of $PM_{2.5}$, was shown to be highly linked to everyday transience [74]. Slezakova et al. (2013) found that concentrations of particulate matter ($PM_{2.5}$ and $PM_{2.5–10}$) and polycyclic aromatic hydrocarbons (PAHs) at urban sites were 380% and 370% higher, respectively, compared to remote locations [75]. Vehicular emissions were identified as the major contributor to particulate PAHs in urban areas. The elevated levels of $PM_{2.5}$-bound PAHs at urban sites exceeded health-based guideline levels, thus indicating increased health risks. This includes an increased risk of developing lung cancer due to long-term exposure to these pollutants. In addition to lung cancer, exposure to elevated levels of particulates and PAHs from vehicular emissions may also contribute to other health problems such as respiratory diseases (e.g., asthma and chronic obstructive pulmonary disease) and cardiovascular diseases.

Taxi drivers typically spend extended periods on the road, exposing them to elevated levels of vehicular emissions and potentially increasing their susceptibility to health risks. A study conducted on 50 taxi drivers in Paris by Hachem et al. (2021) revealed that approximately 50% of participants reported experiencing at least one chronic respiratory or allergic disease [76]. This finding suggests a notable prevalence of adverse health effects associated with occupational exposure to vehicular emissions among taxi drivers. Taxi drivers experienced mucosal irritation during the year 2020, with significant percentages reporting nose (42%), eye (38%), and throat (36%) irritation. This suggests that exposure to particulates from vehicular emissions may lead to acute respiratory symptoms. Consistent findings from occupational epidemiological studies conducted in various locations (Congo [77], Shanghai [78], United Arab Emirates [79]) indicate a higher prevalence of adverse respiratory effects among professional drivers, including asthma, allergic rhinitis, dyspnoea, nasal catarrh, cough, phlegm, and throat pain, compared to non-exposed groups.

Toll collectors, operating within manual toll booths along highways, face heightened health risks due to occupational exposure to vehicular emissions, as illuminated by a study conducted by Nazneen et al. (2023) [80]. This study investigated pollutant concentrations, including PM_1, $PM_{2.5}$, PM_{10}, BC, and UFP, inside toll collector cabins and free traffic sections on a highway, revealing that pollutant levels inside cabins were up to 34% higher than those outside. Toll collectors were notably exposed to elevated levels of BC and UFP, with concentrations reaching up to 2.9- and 1.8-fold higher, respectively, compared to free traffic sections. Furthermore, seasonal variation was observed, with a higher ratio of in-cabin to free section pollutant concentration during summer, attributed to increased cabin door openings due to rising temperatures. Respiratory deposition modelling indicated that toll workers inside cabins are likely to experience pulmonary deposition of fine particles, with levels 75% higher for PM_1 and 50% higher for $PM_{2.5}$ compared to workers in other environments, emphasising their heightened vulnerability to health risks associated with occupational exposure to vehicular emissions.

In a series of studies involving healthy volunteers exposed to UFPs during various transportation activities, intriguing findings emerged regarding acute health effects. Jacobs et al. (2010) reported a minor increase in blood inflammatory cell distribution among cyclists parallel to a traffic corridor, with a mean UFP concentration of 2.9×10^4 particles cm^3, although the distinct role of UFPs compared to $PM_{2.5}$ remained unclear [81]. Strak et al. (2010) observed weak associations between UFP and elemental carbon (EC) exposure during cycling in traffic and acute effects, including decreased lung function and increased exhaled nitric oxide (NO) levels [82]. Vinzents et al. (2005) demonstrated a positive correlation between oxidative DNA damage and cumulative UFP exposure, particularly notable during rush-hour cycling [83]. Additionally, Zuurbier et al. (2011) found that UFP exposure during commuting via automobile or bus resulted in modest effects on respiratory parameters, including a slight decrease in peak expiratory flow and an increase in airway resistance, with notable increases in exhaled NO observed post-exposure [84]. Considering the higher respiratory minute ventilation of cyclists compared to passengers in non-active modes, the potential dose of inhaled UFPs during active transport may be significantly elevated, underscoring the importance of adopting a dose-oriented approach in health effects studies.

Traffic emissions are linked to various health effects. Stroke and heart failure demonstrated specific links with same-day vehicular emission effects, underscoring the expeditious repercussions of transport-related PM exposures on cardiac health. Lall et al. (2011) employed distributed and mono-lag models to scrutinise the nexus between daily fine PM mass from diverse sources and hospitalisations [85]. Their findings elucidated a lack of association between total fine PM mass and non-traffic-related PM sources with overall cardiac hospitalisations, while same-day vehicle fine PM emissions consistently manifested correlations with overall cardiovascular hospitalisations. Schwartz et al. (2002) examined the correlation between traffic-emitted $PM_{2.5}$ and daily mortality rates, revealing that a 1 g/m^3 increase in vehicle-emitted particle concentration in the U.S. precipitated an additional 7000 premature deaths annually [86]. Furthermore, Ostro et al. (2011) employing multisource models, elucidated the significant contributions of vehicles, sulphate from ships, long-distance transportation, and building material dust to the adverse medical consequences of PM, particularly cardiovascular deaths [87]. Numerous studies investigating the effects of vehicular-emitted particulate matter on outcomes such as stroke, all-cause mortality, heart failure, cardiovascular disorders, and respiratory disorders [88–91] have consistently identified traffic-related particulate matter as a causative agent for pulmonary inflammation, cytotoxicity, and cardiotoxicity [92–95]. In view of diverse negative health effects, researchers have been working to reduce the emissions from stationary (e.g., diesel engine sets) and non-stationary sources (vehicles) in various ways such as modifying the engine combustion technologies [96], modifying the catalytic converters to reduce the tailpipe emissions [97,98], and by using alternative fuels [99–101].

3.1.2. Evidence on Health Effects of Particulates from Coal Combustions

The contribution of particulate matter from coal-burning power plants to the overall atmospheric PM levels in major industrialised nations, and the health implications of exposure to particulate matter from such plants have been extensively investigated. Coal combustion emissions predominantly consist of UFPs by number, with variations in number concentration and size distribution influenced by coal types and burning conditions [102–104]. Surprisingly, "clean" coals, like semi-coke coals, known for producing less $PM_{2.5}$ per unit mass fuel combustion, may paradoxically yield higher UFP emissions compared to "dirty" coals like bituminous. The emission profile during stable combustion stages exhibits a greater number of finer particles compared to ignition and fierce combustion stages [105]. The widespread usage of coal, especially in stoves without chimneys, contributes to severe indoor air pollution, with indoor fugitive leakages exacerbating the issue [106–108]. Studies on indoor UFPs in coal-use homes, such as those conducted in rural Guizhou, southwest China, reveal high levels of particles in the 60–80 nm range, indicative of a significant health risk associated with indoor coal combustion emissions [109]. The inhalation of these UFPs can lead to respiratory and cardiovascular diseases, with potential impacts on lung function, inflammation, and oxidative stress, particularly among vulnerable populations residing in these indoor environments.

A study by Luo et al. (2022) investigated that indoor UFP concentrations in coal-burning homes were found to be approximately one order of magnitude higher than outdoor UFP levels, with total concentrations reaching up to 1.64×10^5 cm^{-3} [102]. The indoor-to-outdoor ratio of UFPs in coal-burning households was approximately 6.4, indicating substantial indoor sources. During the coal ignition period, particle number concentration increased by ~5 fold, underscoring the dynamic nature of UFP emissions. Indoor coal combustion was identified as the predominant source, contributing over 80% of indoor UFPs, emphasising the serious health hazards associated with UFP exposure.

The US EPA's Integrated Science Assessment (ISA) department conducted a study showing that interim exposure to secondary sulphate and fine PM from power plants was linked to cardiorespiratory medical complications [110]. However, the available data lacked systematicity and sufficiency. Concurrently, the Committee on the Medical Effects of Air Pollutants (COMEAP), United Kingdom, reported that interim exposure to PM plus sulphate had a "fairly substantial influence" on cardiorespiratory conditions, with a particularly noteworthy impact on mortality [111]. Numerous researchers conducting source apportionment investigations [31–33,42] have established a connection between exposure to particulate matter from coal-burning plants and adverse health outcomes, including lung cancer, all-cause mortality, pneumonia, and cardiovascular deaths [87–89,112]. Munawer M.E. (2018) investigated that the surge in coal combustion for power generation has led to the release of COx, NOx, SOx, PM, and heavy metal pollutants, eliciting a range of health complications, where PM are of significant concern due to their severe health implications, including respiratory diseases like chronic obstructive pulmonary disease (COPD), lung cancer, and asthma, exacerbated by the presence of UFPs [113]. Additionally, the emission of heavy metals from coal combustion plants heightens the risk of cardiovascular diseases, gene mutations, and cancers.

According to Feng et al. (2019), coal combustion is a contributor to the generation of $PM_{2.5}$, a pollutant associated with heightened risks of arrhythmia events [114]. Through high-temperature combustion and atmospheric photochemical processes, coal burning generates detrimental air pollutants, including PAHs and secondary particles [115]. Beijing Environmental Protection Bureau (2014) stated that in Beijing, coal burning has been recognised as the major source of $PM_{2.5}$, contributing to approximately 22.4% of total $PM_{2.5}$ mass in urban areas [116]. In accordance with previous findings, Yu et al. (2018) observed that solid fuel (coal, wood, or charcoal) use was associated with a significantly higher risk of cardiovascular mortality and all-cause mortality in a prospective cohort of 271,217 adults in rural China [117]. Similarly, Folino et al. (2017) reported that exposure to $PM_{2.5}$ from air pollution mixtures with a large contribution from non-industrial combustion was associated with a higher risk of ventricular tachycardia [118].

Studies also showed significant associations between ambient fossil fuel combustion-related pollutant exposures and reduced heart rate variability (HRV) [119,120], prolonged QT interval (The QT interval represents the time it takes for the heart's electrical system to repolarize, or reset, after each heartbeat, a prolonged QT interval indicates a delay in this repolarisation process, which can increase the risk of arrhythmias (irregular heartbeats) and sudden cardiac arrest) [121], depressed ST segment (the ST segment is a portion of the ECG that represents the interval between ventricular depolarisation (contraction) and repolarisation (relaxation). Depression of the ST segment indicates that the heart is not receiving enough oxygen, which can occur due to conditions like myocardial ischemia (reduced blood flow to the heart muscle) or infarction (heart attack)) [122], and increased T-wave alternans (T-wave alternans refers to a pattern on the ECG where the amplitude (height) of the T-wave varies from beat to beat; increased T-wave alternans can be a sign of increased vulnerability to life-threatening arrhythmias, particularly ventricular fibrillation, which can lead to sudden cardiac arrest—it is often associated with underlying heart disease or other cardiac abnormalities) [123]. However, Feng et al. (2019) stated that research on the potential impact of $PM_{2.5}$ from coal burning on arrhythmic risks has been scarce, and their results are largely in line with existing evidence of anthropogenic activity-related sources (coal burning, vehicle exhaust, and secondary particles) on adverse cardiovascular events [114,124–126].

3.1.3. Evidence on Health Effects of Particulates from Diesel Combustions Exhaust

Exposure to diesel particulate matter has been linked to respiratory health hazards, such as asthma and hypersensitive inflammation, while prolonged exposure increases the susceptibility to lung cancer [127–132]. Zerboni et al. (2022) investigated the effects of diesel PM emitted from Euro3 and Euro6 on human BEAS-2B bronchial cells [133]. Their findings revealed that exhaust particulates from Euro3 triggered both normal proinflammatory pathways and cancer-causing routes associated with ignition-emitted particulates. In contrast, Euro6 diesel PM exhibited a less efficient impact in this regard. Wu et al. (2022) emphasised that diesel exhaust particulates (DEPs) can damage alveolar epithelium cells, which serve as a structural barrier protecting against atmospheric exposures by segregating inhaled unwanted chemicals and regulating fluid and ion transfer to maintain alveolar interface fluid equilibrium [134]. DEPs can damage alveolar epithelium cells due to their composition and physical properties [135,136]. These particulates are composed of a complex mixture of substances, including elemental carbon, organic carbon compounds, metals, and other toxic components such as PAHs. When inhaled, these particulates can penetrate deep into the lungs and deposit on the surface of alveoli, where gas exchange occurs. The toxic components within DEPs can induce oxidative stress and inflammation in alveolar epithelium cells, leading to cellular damage and dysfunction. Additionally, the small size of DEPs allows them to easily access and interact with cellular structures, disrupting normal cellular processes and compromising the integrity of the alveolar epithelial barrier. The damage to alveolar epithelium cells caused by DEPs can increase the risk of respiratory diseases such as asthma, COPD, and bronchitis. Additionally, it can exacerbate existing cardiovascular conditions and contribute to the development of cardiovascular diseases such as heart attacks and strokes. Furthermore, prolonged exposure to diesel exhaust particulates may also be associated with an increased risk of lung cancer and other respiratory malignancies. Additionally, Wu et al. (2022) noted that DEPs induce an imbalance in generating ROS and their subsequent removal through protective systems, potentially leading to persistent inflammation in the epithelium and lung fibroblasts [134]. DEPs also inhibit WNT/β-catenin, a critical regulator responsible for cell motility, growth, division, embryogenesis, and essential functions like cell migration, proliferation, stem-cell restoration, differentiation, apoptosis, and genetic stability in epithelial cells [134].

The effects of exposure to DEPs can have various effects on human health and development. An investigation conducted by Acciani et al. (2013), employing a murine exposure model elucidated the absence of pulmonary inflammation when subjected to 1.2 mg/kg of DEPs, juxtaposed with an evident neutrophilic influx following treatment with 6.0 mg/kg of DEPs [137]. Mice subjected to concurrent exposure to DEP and house dust mite (HDM) exhibited heightened airway hyperreactivity, dendritic cell activation, goblet cell metaplasia, lung inflammation, effector/activated T cells, and allergen specific IgE compared to exposures to HDM or DEP in isolation. Investigations into prenatal and postnatal exposures to diesel particulate exhaust have revealed perturbations in developmental processes, sexual maturation, estrogenic profiles, sperm quality, hormonal milieu, spermatogenesis, reproductive and ancillary organ masses, behavioural patterns, monoaminergic framework, manifestation of quasi-immune genetic configurations, histopathological scrutiny of cerebral structures, susceptibility to allergic rhinitis, and the manifestation of inflammation and mutagenic endpoints in rat progeny [138–141].

3.1.4. Evidence on Health Effects of Particulates from Household Wood Combustors' Exhaust

In regions characterised by severe or mild freezing climates, residential wood-burning furnaces have been shown to markedly augment ambient PM concentrations [142–147]. Elevated levels of PM resulting from the combustion of firewood in residential furnaces have been correlated with respiratory symptoms and exacerbations, particularly in children [148–150]. While the connection between environmental wood-burning exhaust PM and cancer is still being studied, research has shown their impact on health. Wood smoke from combustion contains carcinogenic compounds, such as fused-ring stable hydrocarbons. Prolonged indoor exposure to wood smoke has been linked to an increased susceptibility to cancer development [151]. Improved cookstoves, compared to their conventional counterparts, have demonstrated efficacy in mitigating various health impacts, including symptoms of eye irritation, angina, breathlessness, and paroxysmal coughing [152,153]. According to Pratiti et al. (2020), using high-quality cookstoves can be an effective way to improve indoor air quality and reduce hypertension by up to 16% [154]. In addition, Jamali et al. (2017) found that the use of improved cookstoves was less harmful compared to conventional alternatives, resulting in a reduction in symptoms such as cough, breath shortness, chest tightness, asthma attacks, and irritated eyes [155].

Exposure to $PM_{2.5}$ has been linked to elevated blood pressure, increased respiratory symptoms such as asthma and cough, and lower birth weight in newborns, while prolonged exposure to cooking oil fumes may lead to a decline in lung function among individuals. Pratiti et al. (2020) further emphasised that human exposure to $PM_{2.5}$ is associated with elevated systolic and diastolic blood pressure, as well as an increased propensity for asthma, cough, wheezing, and phlegm [154]. Pregnant women exposed to household air pollution, particularly from wood combustors used for cooking, may experience elevated levels of $PM_{2.5}$ and CO during pregnancy [156]. A study conducted in Dar es Salaam, Tanzania, found that maternal exposure to $PM_{2.5}$ emissions from household wood combustors was associated with a reduction in birth weight in newborns [156]. This observation underscores the potential adverse health effects of household air pollution on maternal and neonatal outcomes, emphasising the need for targeted interventions to mitigate exposure to harmful pollutants from wood combustion sources. Du et al. (2017) conducted an experiment in China wherein, following 48 hours of employing the conventional Chinese household food preparation method (using wood burners), a substantial decline in lung function was observed among healthy young students [157]. Notably, exposure to cooking oil fumes for approximately 20 min, even at twice the particulate levels observed in Chinese home cooking, resulted in minimal impact on cardiac, proinflammatory, or oxidative-related diseases that did not reach statistical significance.

Some studies have associated household wood combustors' $PM_{2.5}$ emissions with cardiovascular [91] and respiratory morbidity [150], asthma exacerbations [150,158,159] bronchitis [160], and a reduction in lung immunity [161,162]. Distinct combustion sources exhibit diverse effects on lung reactivity, with gender influencing responses. For example, Seagrave et al. (2005) exposed male and female mice to hardwood smoke and diesel exhaust emissions [161]. Diesel exhaust-treated females exhibited lower levels of proinflammatory polypeptide-2 in macrophages. Both diesel exhaust-treated females and males demonstrated lower tumour necrotic expression extent, whereas hardwood smoke-treated males exhibited minor elevations, and diesel exhaust emissions had no effect on overall glutathione in both species. However, hardwood burning reduced glutathione in females, with increases observed in males at lower levels of treatment but not at higher exposures.

3.1.5. Evidence on Health Effects of Particulates from Earth's Crust Dust

Natural dust particles, originating from sources like soil erosion and volcanic activity, contribute significantly to atmospheric particulate matter [163]. For instance, volcanic eruptions can emit millions of tons of ash and dust particles into the atmosphere annually, with particle sizes ranging from micrometres to millimetres. Estimates suggest that the annual emission volume of mineral dust caused by wind erosion on a global scale range from 1 to 5 billion tons [164,165]; this substantial amount of dust contributes significantly, representing approximately 30–50% of the total aerosols released into the Earth's atmosphere [166,167]. On the other hand, anthropogenic sources, such as industrial processes and transportation, emit significant amounts of $PM_{2.5}$ and UFPs, which are smaller in size and have been linked to various health problems. Dust emanating from diverse sources such as dunes or volcanic eruptions has emerged as a growing concern for public well-being [168]. The dispersion of particles from dust storms can vary widely depending on various factors such as wind speed, atmospheric conditions, and the size of the particles. Generally, larger particles tend to settle closer to the source of the dust storm, while smaller particles, such $PM_{2.5}$ and UFPs as can be carried over long distances by winds. In some cases, these particles can travel hundreds or even thousands of kilometres from their source [169], leading to regional or even global impacts on air quality, visibility, and public health. The dispersion of dust particles is influenced by atmospheric dynamics, including wind patterns and atmospheric stability, which can transport the particles over large distances before they eventually settle out of the atmosphere.

A plethora of antecedent research findings accentuates the adverse health impacts of synthetic particulates [170]. Recent studies underscore the deleterious health effects associated with wind cyclones, as studies utilising laboratory animals (Male Sprague Dawley rats obtained from the National Laboratory Animal Breeding and Research Center, Taiwan) have demonstrated the harmful impacts of particulates carried by windy dust cyclones [171,172]. Epidemiology studies have corroborated the negative impact of dust storms on public health, encompassing various demographics and employing analytical measures [173,174]. A systematic investigation by Aghababaeian et al. (2021) comprehended the health impacts of dust storms worldwide, highlighting both short- and long-term effects [175]. Short-term impacts encompass increased mortality, emergency medical dispatches, hospitalisations, and respiratory symptoms, while long-term effects include pregnancy complications, cognitive impairments, and birth problems. The study underscored the severe consequences of dust storms on cardiovascular and respiratory health, emphasising the importance of frequency in exacerbating health risks.

In an examination of Asian dust cyclones conducted by Chan et al. (2008), in Taiwan, a comparison of pre- and post-storm hospital visits revealed that during storm-affected periods in Taipei, atmospheric PM_{10} levels exceeded 90 g/m^3, leading to an increase in cardiorespiratory hospital visits [176]. Employing a *t*-tests model, it was observed that urgent hospital admissions due to coronary artery disorder increased by 35%, stroke or cerebrovascular disorder increased by 20%, and chronic obstructive pulmonary disease during dust storms significantly rose by 20%. Notably, urgent medical requirements for cardiac illnesses surged by 67% for each episode during 39 Asian heavy storm incidents. Analogous studies examining the health effects of particulates from the Earth's crust implicated earth's crust dust in infectious diseases [177–179], cardiac mortality, and all-cause mortality [174,180,181], chronic obstructive pulmonary disease and respiratory morbidity [182–184], pneumonitis [171,185], compromised lung functionality [186], asthma [187–189], and pneumonia [190,191]. Sajani et al. (2007) reported significant evidence of higher respiratory death rates among individuals aged 75 and over in the context of the Saharan desert dust [192].

3.2. Deposition of Ultrafine Particles in Lungs

The general process of the deposition of PM and UFPs includes interception, impaction, sedimentation, and diffusion [193]; the particulates follow these four mechanisms to travel and deposit in the human lungs airways [194]. Interception occurs when the edges of entering particles, such as fibre-shaped ones (e.g., asbestos), adhere to the airway surface, with the particle length influencing the deposition position. For instance, an asbestos particle with an aerodynamic diameter of 1 μm and a cross-sectional length of 180 μm will deposit on the branched bronchi. In impaction (also known as inertial impaction), the mass of the particle and the velocity of air play crucial roles. As per the law of inertia, particles tend to maintain their original path, but since airways possess bends, particle mass may hinder their responsiveness to air velocity, compelling them to deposit on the airway surfaces. Sedimentation occurs for particles with an aerodynamic diameter $\geq$ 0.5 µm, wherein the resistance of air and gravitational forces outweigh the buoyancy of the particles, leading to deposition on bronchi surfaces. Diffusion takes place due to the Brownian Motion of particles < 0.5 µm, where their random motion fortuitously causes them to attach to lung airway surfaces, representing a prominent deposition phenomenon.

The deposition of UFP through diffusion is contingent upon particle size, with potential sedimentation occurring in the alveolar, nasal, and tracheobronchial regions (Figure 3) [195]. UFPs with a size of 0.001 µm primarily deposit (approximately 90%) in the nasal, pharyngeal, laryngeal regions, while exhibiting approximately 20% and 0% deposition in the tracheobronchial and alveolar regions (Figure 3) [196]. Similarly, particles with a size of 0.01 µm display the highest deposition efficiency in the alveolar region, with moderate deposition observed in the nasopharyngeal and tracheobronchial regions. Furthermore, as the particle size increases from 0.1 µm to 10 µm, deposition efficiency in the alveolar and tracheobronchial regions decreases, subsequently surging to approximately 80% deposition efficiencies in the nasopharyngeal region. Thus, a compelling imperative exists for further research endeavours in the sampling and collection of ultrafine particles to comprehend their implications on human health.

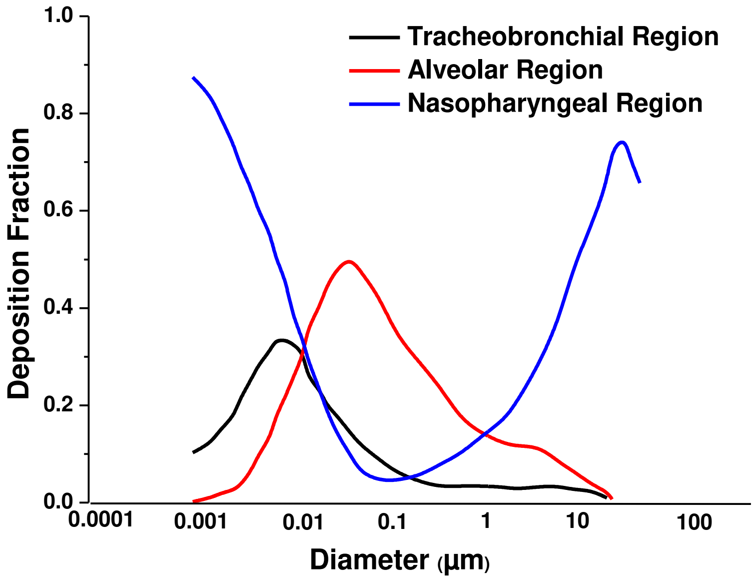

Figure 3. Deposition of particles according to size distribution.

4. Part II: Measurement of Particulate Matter

Particle size and concentration are crucial factors in determining air quality standards for PM. Acquiring spatially resolved data on ambient UFPs is crucial due to their significant spatial variability within cities, which surpasses that of $PM_{2.5}$ and PM_{10} [197]. However, challenges persist regarding the sparse availability of UFPs data in both spatial and temporal dimensions, hindering future research in this area. Furthermore, the lack of standardised measurement methods for ambient UFPs concentrations exacerbates the problem. Variations in measurement results among instruments employing different operating principles further complicate matters. Typically, PNC and particle number size distribution (PNSD) serve as metrics for quantifying ambient UFPs, with condensation particle counters (CPCs) and scanning mobility particle sizers (SMPS) being the most commonly used instruments [198]. However, the sophisticated and costly nature of these instruments impedes the establishment of nationwide UFPs monitoring networks. Encouragingly, recent developments have yielded low-cost UFP sensors capable of providing approximate measurements of UFPs PNC [199], potentially facilitating the expansion of monitoring networks. Additionally, various modelling approaches have been proposed to estimate UFPs PNC in ambient air, offering alternative solutions for enhancing the resolution of UFPs exposure assessments [200,201]. These advancements hold promise for advancing our understanding of ambient UFPs and their implications for public health.

Instruments designed for particle measurement can be systematically categorised into two categories, those that elucidate size distribution and those that gauge concentration (Figures 4 and 5). In concentration methods, PM concentration can be assessed through measurements of mass, number, and surface area. These parameters serve as vital indicators for evaluating PM exposure and potential health effects. Various instruments are employed to conduct these measurements, each based on distinct principles, including gravimetric, optical, microbalance, and electrical charge methodologies. The gravimetric method determines particle mass concentration by weighing filters before and after sampling, with filters typically conditioned under controlled temperature and humidity conditions [202,203]. This method collects particles across various size fractions, unless larger particles are removed by cyclones or impactors [203].While particle sampling on filters provides chemically analysable samples, it lacks resolution for identifying fast processes [202]. Additionally, cascade impactors are commonly used in gravimetric measurements to investigate particle size distribution [203].

In optical detection methods, aerosol particles scatter and absorb light when illuminated by a beam, allowing for the calculation of light extinction through the combination of scattering and absorption [203]. Light-scattering instruments can be based on dispersion photometers or scattering photometers, measuring scattered light intensity at different angles [203,204]. Instruments such as the Respirable Aerosol Monitor (RAM) utilise scattering photometry to measure scattered light from all particles in the detection volume [4]. Additionally, light absorption by aerosols can be measured using methods like the difference method, filters, photoacoustic spectroscopy, and laser-induced incandescence (LII) [203]. Spotmeters and Aethalometers are commonly used instruments for measuring light absorption by carbonaceous aerosols [203,205]. Other techniques include the Photoacoustic Soot Sensor (PASS) and LII, which measure absorption through particle heating and incandescence [203,206]. Optical Particle Counters (OPCs) and CPCs utilise light-scattering principles to count and size particles, with CPCs enlarging particles through condensation for detection [203]. Instruments based on light extinction, such as Cavity Ring Down (CRD) systems and Opacity Meters, measure light transmitted through aerosols to quantify particle concentration [203,207,208]. Overall, these methods provide crucial insights into aerosol characteristics and behaviour in atmospheric studies.

Microbalance methods employ sensitive balances or microbalances to precisely measure particle mass. Particles are deposited onto a weighing substrate, and the resulting mass change is accurately measured. Microbalance instruments offer high sensitivity and can detect very low PM concentrations, making them valuable for laboratory research and calibration purposes. Giechaskiel et al. (2014) outlined the utilisation of oscillatory microbalances in particle collection for mass determination, with microbalances relying on changes in resonance frequency for PM measurement [203]. Two primary instruments employing this method are the Tapered Element Oscillating Microbalance (TEOM) and the Quartz Crystal Microbalance (QCM). TEOM operates by detecting frequency alterations in a tapered quartz wand connected to a sampling filter, particularly useful in real-time PM_{10} and $PM_{2.5}$ measurements during biomass combustion [202]. Although TEOM faces challenges with humidity and pressure changes, it remains reliable for specific applications, as demonstrated by its continuous PM_{10} sampling in urban areas [209]. On the other hand, QCM relies on the piezoelectric property of quartz crystals to detect resonance frequency changes induced by particle deposition through electrostatic precipitation [203]. This technique offers another avenue for precise PM measurement and has been utilised in various research contexts [203,210].

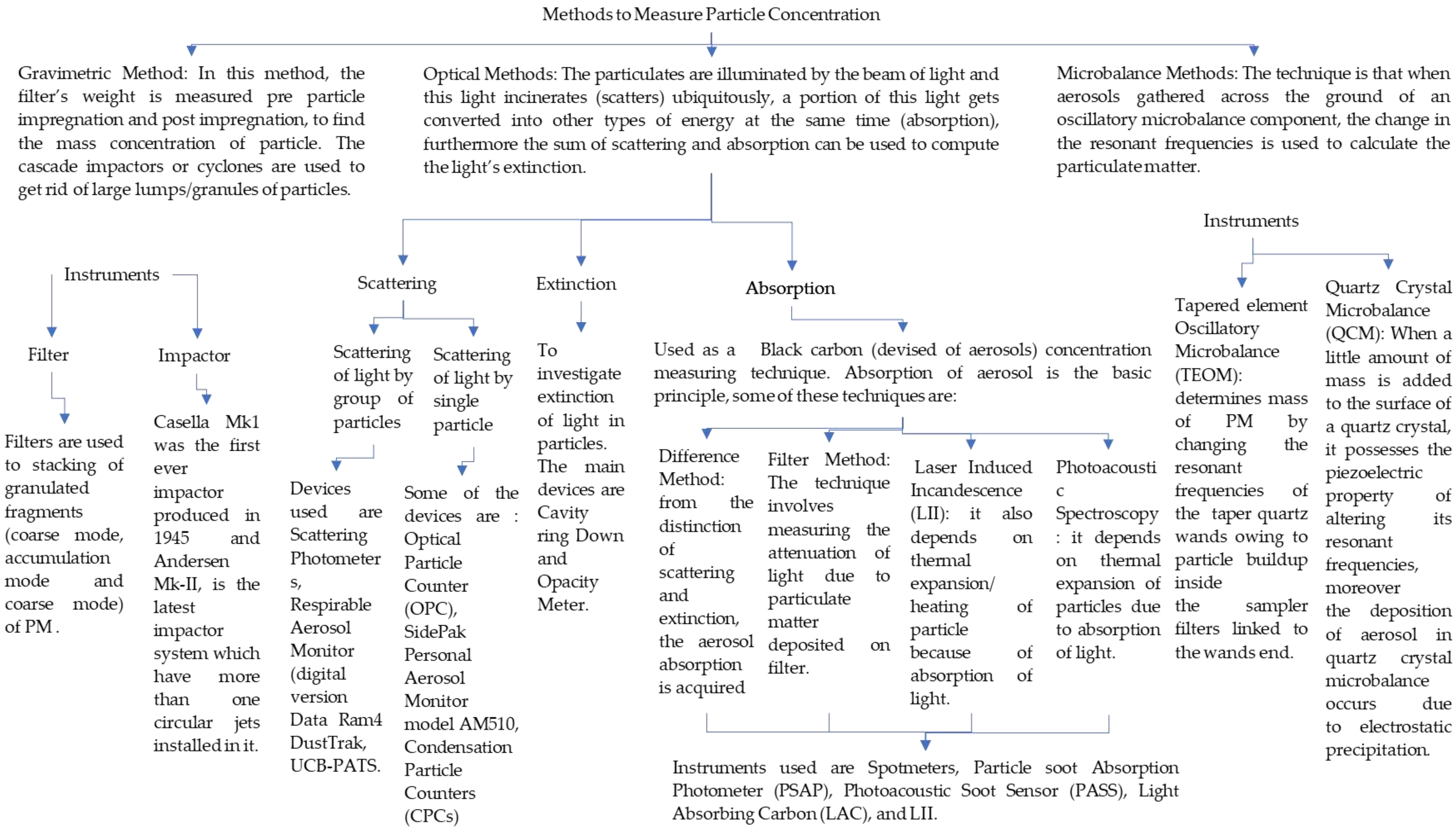

Figure 4. Methods to measure particle concentration [4,202,203,207–209,211–217].

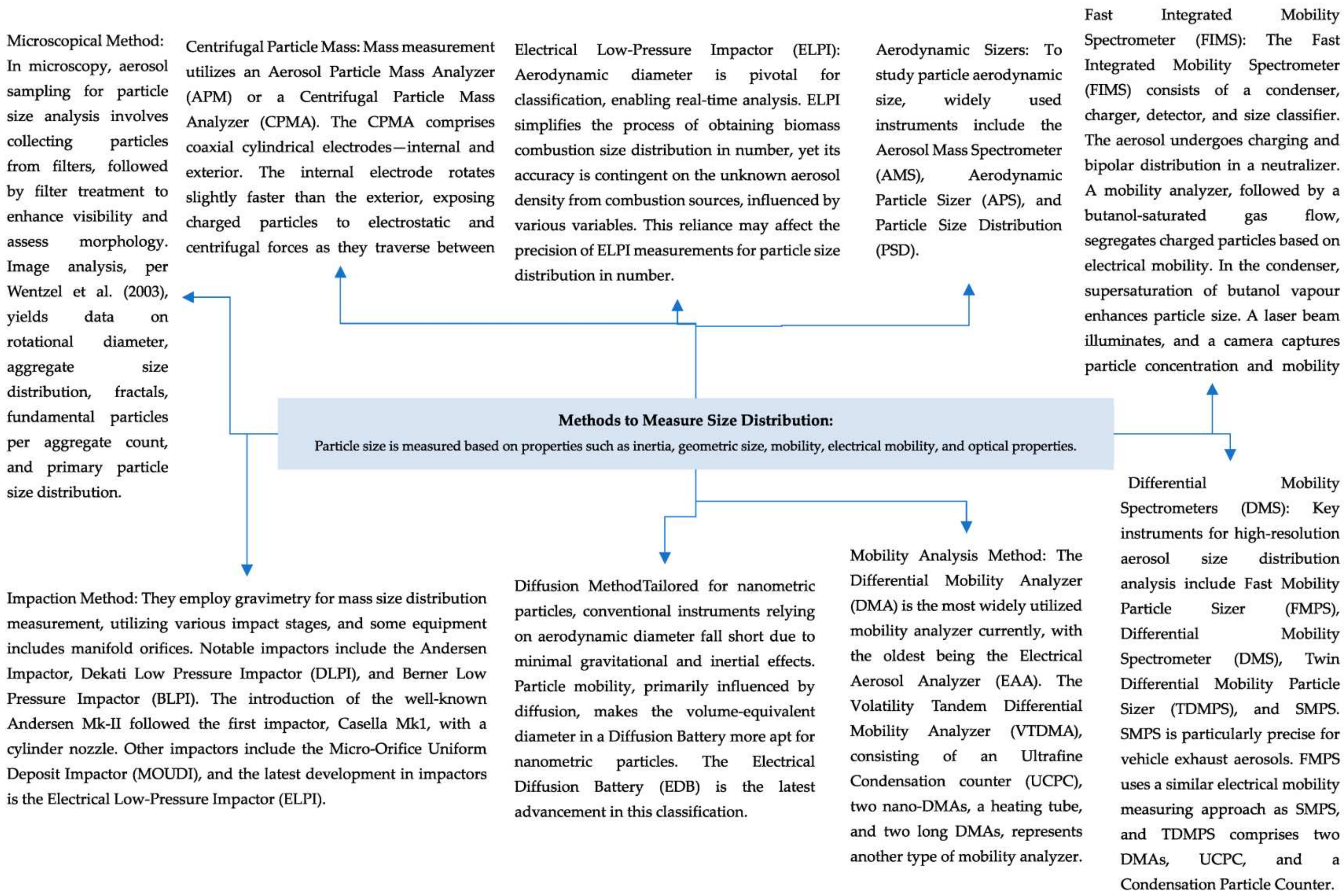

Figure 5. Methods to measure size distribution [218–228].

Figure 4 shows the size distribution measurement methods which assess aerosol size in terms of diameter (mobility, aerodynamic, etc.) and concentration. Particle size is determined based on properties such as geometric size, inertia, mobility, electrical mobility, and optical properties [203]. Several instruments are utilised in combination for size distribution measurement, including microscopy, impactors, diffusion batteries (EDB), mobility analysers, centrifugal particle mass analysers (CPMA), differential mobility spectrometers (DMS), fast integrated mobility spectrometers (FIMS), and electrical low-pressure impactors (ELPI) [203].

Microscopy involves particle collection from filters followed by preparation to enhance visibility, providing insight into particle dimensions and morphology [4]. Impactors, such as the Andersen Impactor and the electrical low-pressure impactor (ELPI), classify particles based on inertial classification, collecting particles of various sizes across multiple stages [202,203]. Diffusion batteries and electrical diffusion batteries separate particles by mobility, with the latter offering improved suitability for nanometric particles [4]. Mobility analysers like the Electrical Aerosol Analysers (EAA) and Differential Mobility Analysers (DMA) classify particles based on electrical mobility, enabling precise size distribution measurements [203].

Centrifugal measurement methods, including CPMA and APM, classify particles based on their mass-to-charge ratio or aerodynamic diameter, offering real-time mass concentration determination without the need for particle collection [203]. Differential mobility spectrometers (DMS) and fast mobility particle sizers (FMPS) provide high-resolution size distribution measurements, particularly effective for analysing aerosols from vehicle exhaust and biomass combustion [202,203,225]. The fast integrated mobility spectrometer (FIMS) utilizes a charger, size classifier, condenser, and detector to assess particle mobility diameter, offering real-time insights into particle concentration and size [203,226,229].

Electrical low-pressure impactors (ELPI) classify particles by aerodynamic diameter, measuring concentration and size distribution in real-time, although the technique's accuracy may be affected by aerosol density variations [4,203,230]. Finally, aerodynamic sizers such as the Aerodynamic Particle Sizer (APS) and the Aerosol Mass Spectrometer (AMS) measure aerosol size distribution by analysing particle acceleration or thermal vaporisation, offering comprehensive insights into particle composition and size distribution [225,231].

4.1. Collection of Particles

The selection of collection strategies is heavily contingent upon the microenvironments from which particles originate. Indoor settings, for example, may pose limitations for accommodating large sampling instruments due to potential noise concerns [232]. Similarly, in densely populated roadways or polluted open spaces, deploying small-volume sampling instruments with reduced pump capacity may encounter drawbacks owing to elevated PM concentrations, possibly requiring expeditious filter changes [232].

4.1.1. Collection/Sampling of Fine Particles

Particulate collection strategies have been classified into three primary categories: the first encompasses higher proportion (high-volume) sampling instruments, the second pertains to small proportion (small-volume) sampling instruments, and the third is dedicated to cascade impactors. The high-volume sampling instruments are designed to capture particulate matter, particularly $PM_{2.5}$, swiftly and efficiently. They have high flow rates ranging from 16.7 to 30 L per minute. They excel at collecting substantial quantities of particulates within shorter time intervals and consume electricity comparable to household electrical appliances. Primarily used in outdoor settings, notably roadside locations, these samplers play a crucial role in gathering particulate matter effectively [49–54]. Small/medium-volume sampling instruments are dual impactors capable of collecting both $PM_{2.5}$ and PM_{10} particles at a flow rate of 5 L per minute. They are ideal for environments with high particle concentrations and are suitable for continuous sampling over short periods, such as months. These compact samplers are particularly useful for indoor settings due to their low noise emission, although their lower flow rate may require longer sample periods [55]. Cascade impactors are sophisticated devices with four stages designed to capture particles of different sizes, including $PM_{0.1}$, $PM_{1.0}$, $PM_{2.5}$, and PM_{10}. They utilise PUF substrate and Teflon filters for efficient collection and have a high flow rate of 900 L per minute, making them versatile for use in both indoor and outdoor environments. [56,57].

High-Volume Sampling Instruments

Envirotech APM-550: The Envirotech APM-550 instruments are equipped with high flow rates ranging from 16 to 30 cubic feet per minute (cfm) or approximately 450 to 850 L per minute (L/min). These flow rates enable efficient sampling of $PM_{2.5}$ particles in ambient air, ensuring thorough air quality monitoring. Additionally, it incorporates advanced technologies such as beta attenuation and gravimetric methods for accurate and reliable measurement of particulate matter concentrations [233]. Further, it utilizes a high-volume air sampling mechanism, allowing them to draw a large volume of ambient air through the sampling inlet over a specified period. This high flow rate enhances the collection efficiency of particulate matter, especially fine particles like $PM_{2.5}$, ensuring representative sampling. The sampler is equipped with precision filter media designed to efficiently capture particulate matter from the sampled air. These filter media are typically made of materials such as quartz or Teflon, which have high particle retention capabilities and minimal interference with the sampled aerosols. Advanced model of this instrument may feature real-time monitoring capabilities, allowing users to monitor $PM_{2.5}$ concentrations continuously. They may also include data logging functionalities, enabling the storage of sampled data over time for further analysis and reporting.

The instrument APM-550 with Whatman QM-A filters with a diameter of 47 mm was used in the toxicological study. Islam et al. utilised the APM550 instrument in their study aiming to identify and investigate the toxicological aspects of PAHs in PM. Additionally, it explored the interplay between these pollutants and climatic factors, while also conducting quantitative source apportionment to aid in mitigation strategies [234].

The APM550 is compact and portable, making it convenient for conducting personal exposure measurements and monitoring $PM_{2.5}$ levels in various indoor and outdoor environments [235]. Habil et al. (2016) studied the utilisation of APM-550 for measuring $PM_{2.5}$ concentrations during personal exposure assessments of school children, office workers, and residents in urban Agra, India, not only sheds light on the daily exposure characteristics to fine particles but also reveals potential sources and their impact on human health, emphasising the critical role of accurate and portable monitoring instruments like APM-550 in understanding and mitigating the adverse effects of ambient particulate matter on respiratory and cardiovascular systems [236].

The Envirotech APM-550 employs a manual technique for particulate collection ($PM_{2.5}$), adhering to USEPA-standardised designs of impactors for external environmental assessment (Figure 6) [237]. Functioning as an omni-directional intake, the APM-550 ensures clear aerodynamics cut-points for particulates > 10 μm, redirecting particles < 10 μm in the air streams to a secondary impactor with an aerodynamics cut-point of 2.5 μm. Subsequently, particles exiting the $PM_{2.5}$ impactor pass through a Teflon membrane filter with a diameter of 47 mm, effectively trapping minute particulates [238]. The system maintains a constant collection rate of 1 m3/hour through a critical orifice, preventing filter choking. The inclusion of a Dry Gas Meter provides a transparent indication of the total collected air volume [239].

Figure 6. Envirotech APM-550 NL [237].

Model ADS-2062E—Intelligent Integrated Air Sampler (AMAE Co., Ltd., Shenzhen, China):

The ADS-2062E Intelligent Integrated Air Sampler is a medium-volume sampler that is usually used to measure $PM_{2.5}$ for cytotoxicological studies. This sampler has an intricate internal structure to effectively collect $PM_{2.5}$ particles from the ambient air. The sampler is equipped with an air intake mechanism that draws ambient air into the sampling chamber at a controlled flow rate. Upon entry, the air passes through a series of filters designed to remove larger particles and debris, ensuring that only fine particulate matter, including $PM_{2.5}$, enters the sampling pathway. Within the sampler, the incoming air stream undergoes a process of particle separation to isolate $PM_{2.5}$ particles from other airborne contaminants. This separation mechanism may involve inertial impaction, diffusion, or cyclonic action, depending on the specific design of the sampler. These mechanisms exploit differences in particle size, mass, and inertia to selectively capture $PM_{2.5}$ particles while allowing other particles to pass through. The ADS-2062E utilizes a specialised collection medium, typically a filter substrate with fine pores or a membrane filter, to capture $PM_{2.5}$ particles suspended in the air stream. This collection medium is positioned strategically within the sampler's sampling pathway to intercept and retain $PM_{2.5}$ particles effectively. Researchers can program the sampler to determine the sampling duration and interval according to study requirements [240]. The sampler may operate continuously or in predefined sampling cycles, with the duration and interval adjusted to optimise $PM_{2.5}$ sampling efficiency while minimising resource consumption. As the ambient air passes through the collection medium, $PM_{2.5}$ particles are deposited onto the surface of the filter substrate or membrane. Over time, $PM_{2.5}$ particles accumulate on the collection medium, forming a representative sample of airborne particulate matter for subsequent analysis.

The instrument incorporates an integrated elevated pressure and thermal sensor, which autonomously computes and outputs suitable flow conditions. With explicit calibration authorisation, the operator retains control over the accuracy of sample flow, and as an additional feature, automated heating is facilitated at reduced temperatures. Achieving a steady current-controlled sampling rate ranging from 0.1 L/min to 1.0 L/min is executed through the implementation of a closed-loop method [241].

In a study by Guo et al. (2023), this sampling method was used to collect air samples (specifically $PM_{2.5}$) which facilitated the analysis of the pollution characteristics, dietary intake levels, and health effects of 16 PAHs in vegetables, fruits, and meat products in Nantong City, China [242]. The study aimed to determine PAHs content, pollution level, carcinogenic risk, and correlation of soil and local atmospheric environment in the crop irrigation area; however, to accomplish the aim of the research, soil and food samplings were also performed using different methods [242].

The AMAE ADS2062E air sampler served as a critical tool in a pioneering study investigating $PM_{2.5}$-bound environmentally persistent free radicals (EPFRs) in Zhengzhou [243]. Its medium-volume sampling capability, combined with the use of quartz fibre filters, facilitated precise collection of $PM_{2.5}$ samples, enabling thorough examination of pollution levels, seasonal variations, and health risks associated with EPFRs. By providing representative samples over time, the ADS2062E air sampler contributed essential data to understand the contamination status of $PM_{2.5}$-bound EPFRs in Zhengzhou, offering valuable insights for local air pollution control efforts and strategies to mitigate exposure risks to public health in central China.

Song et al. (2020) employed this model to explore cytotoxicological reactions across three pivotal cell lines: BEAS-2B human broncho epithelium cells, A549 alveolus cell line, and Kmb17 human embryonic lung fibroblast cells, upon exposure to collected samples of $PM_{2.5}$ particles [244]. This sampler proves ideal for capturing both particulate and gaseous contaminants amidst disorganised exhaust and varying air pressure conditions, particularly in environmental assessments [244]. Figure 7 illustrates the structure of the ADS-2062E—Intelligent Integrated Air Sampler utilised in the study.

Figure 7. Structure of ADS-2062E—Intelligent Integrated Air Sampler [241].

This sampling methodology allowed for the precise collection of $PM_{2.5}$ samples, which were then utilised to expose the transgenic mice to real-world $PM_{2.5}$ concentrations [245]. Fu et al. (2020) aimed to investigate the effects of $PM_{2.5}$ on intestinal and brain injury, as well as bacterial community structure in the intestine and faeces of APP/PS1 transgenic mice exposed to $PM_{2.5}$ for eight weeks in Taiyuan, China, due to the emerging recognition of $PM_{2.5}$ as a risk factor for neurological disorders and its impact on the gut bacterial community structure in Alzheimer's disease patients [245]. This sampler ensured the reliability and accuracy of $PM_{2.5}$ sampling, enabling researchers to assess its effects on intestinal and brain tissues, as well as bacterial community structure, providing valuable insights into the potential health impacts of $PM_{2.5}$ exposure.

High Volume Sampler TH-1000CII, Wuhan Tianhong, China: The High-Volume Sampler TH-1000CII (Figure 8) boasts impressive technical specifications, including a sampling flow rate error rate of less than 2% [246]. Utilising an automatic constant current system with an adjustment accuracy of 0.01/min and a constant current stability exceeding 0.5%, this instrument ensures precise and stable sampling conditions. Additionally, it possesses the capability to measure and record atmospheric pressure, temperature, system load, flow rate, and other parameters, allowing for comprehensive data collection and analysis. With the ability to collect not only $PM_{2.5}$ but also Total Suspended Particulates (TSP) and PM_{10}, the TH-1000CII is versatile, making it suitable for a range of applications including environmental monitoring, assessment sampling, and scientific research experiments [247]. Notably, its standout feature is the super large flow pump, which enables efficient and high-volume sampling, distinguishing it as an invaluable tool for sampling in various environmental contexts. Sun et al. (2009) utilised this instrument, employing quartz membranes for the collection of $PM_{2.5}$ [248]. In their study, they highlighted that certain toxicological investigations have indicated that prolonged exposures to $PM_{2.5}$ can lead to lung fibrosis. However, they emphasised the absence of evidence suggesting that brief exposures could result in the development of pulmonary fibrosis after exposure.

Figure 8. Visual representation of TH1000CII instrument [249].

Zhang et al. (2017) employed the same sampling technique in their biological study, gathering $PM_{2.5}$ at a flow rate of 1.05 m^3/min on quartz filters measuring 8 × 10 inches [250]. Their hypothesis centred on the unknown acute metabolic consequences and toxicity pathways associated with environmental $PM_{2.5}$ exposure. Through this method, Zhag et al. (2017) investigated spontaneous metabolic alterations and potential impacts on metabolic processes in rats after intratracheal inhalation of $PM_{2.5}$ [250]. The study stamps the usefulness of THC1000CII instrument in the processes underlying the toxic effects of $PM_{2.5}$.

Small/Medium-Volume Sampling Instruments

Tianhong TH-150C $PM_{2.5}$ Sampler Instrument: The Tianhong TH-150C $PM_{2.5}$ Sampler is characterised by a medium-volume sampling capacity, featuring a flow rate of 100 L/min. Distinguished by its advanced technological capabilities, this instrument incorporates automatic constant current functionality and comprehensive data processing throughout the sampling process. Notably, beyond its primary function of $PM_{2.5}$ sampling, it offers versatility by accommodating sampling for PM_1, PM_5, and PM_{10}, thus enhancing its utility across diverse applications. A notable feature of the TH-150C is its ability to integrate medium flow PM sampling with dual-channel gas sampling (0.1–1) L/min, enabling concurrent sampling of particulate matter and atmospheric constituents separately. This multifunctional design streamlines sampling procedures, facilitating efficient and simultaneous data collection for various analytical purposes. The Tianhong TH-150C Instrument, is manufactured by Wuhan Tianhong Environmental Protection Industry Co., Ltd. Located in Donghu New Technology Development zone, Wuhan, China. It is characterised by low noise and equipped with intelligent microcomputer capabilities, serves as an advanced total suspended particle sampler (Figure 9). Zhang et al. (2021) employed this instrument for $PM_{2.5}$ sampling at a flow rate of 100 L/min, utilising 90 cm-sized films of polypropylene and quartz for the collection of $PM_{2.5}$ particles [251]. This study, conducted to provide scientific insights to the pollution prevention board in Liaocheng, China, aimed to investigate the sources and characteristics of $PM_{2.5}$ at various pollution levels in the region. In a related study, Huang et al. (year) explored the temporal distribution of $PM_{2.5}$ over a one-year period (23.5 h per day, across four different seasons in Beijing). Quartz membranes with a diameter of 90 mm served as filters for $PM_{2.5}$ sampling [252]. Following sampling, each quartz filtering membrane was individually placed into Petri dishes and promptly stored at 20 °C until being weighed and analysed.

Figure 9. Visual representation of Tianhong TH-150C Instrument [253].

In a study by Ren et al. (2020) particulate sampling was conducted using a 47 mm-sized quartz filter membrane [254]. The investigation focused on elucidating the molecular mechanisms underlying the association between maternal exposure to ambient $PM_{2.5}$ and congenital heart defects in offspring. They hypothesised that the aryl hydrocarbon receptor (AHR) mediates excessive ROS production, thereby contributing to the cardiac developmental toxicity of $PM_{2.5}$. The Tianhong TH-150C $PM_{2.5}$ sampler played a pivotal role in this study by enabling accurate and reliable collection of ambient $PM_{2.5}$ samples, facilitating the assessment of maternal exposure levels and subsequent analysis of potential molecular mechanisms underlying cardiac developmental toxicity [254].

High-Volume Cascade Impactor

ChemVol Model 2400 High Volume Cascade Impactor: In the ChemVol Model 2400 High Volume Cascade Impactor, a poly-urethane foam (PUF) layer is influenced with differently sized range of particles (Figure 10). The environmental air enters the sampler from the top section, traversing through multiple sampling layers before exiting at the bottom. To prevent rainwater ingress, a rain cap is incorporated, and a supportive tripod maintains the specimen entry point at a standard height of 1.5 m to 2 m. A robust blower generates the necessary vacuum to sustain the intended flow rate of 900 L/min. Calibration of volume inflow rates within the instrument is facilitated by an in-check flow sensor located at the bottom of the sampling instrument. Functioning as a passive collection medium, the PUF layer prevents particulate bounce during sampling, ensuring that captured particles remain in place for subsequent analysis [248]. With its enhanced collection capacity, the PUF layer efficiently traps a significant volume of PM, making it well suited for environments with varying particle concentrations. Moreover, the PUF layer's design allows for easy removal, facilitating the extraction of collected particulates for comprehensive laboratory analysis. Overall, the PUF layer contributes to the instrument's effectiveness in studying the composition and characteristics of airborne particles in diverse environmental settings [255].

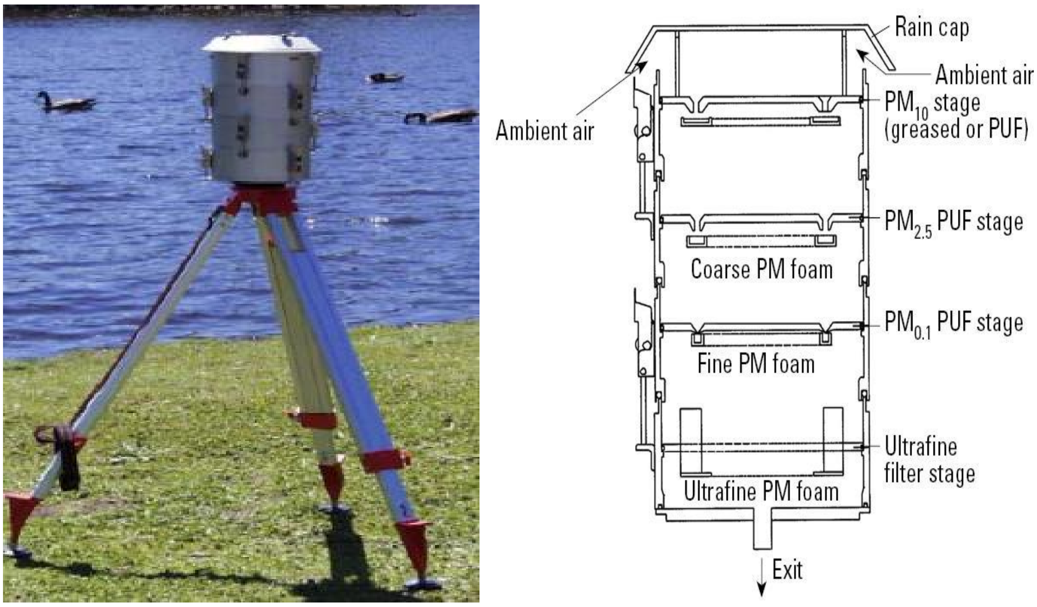

Figure 10. ChemVol Model 2400 High Volume Cascade Impactor in a fieldwork sampling, comprising a sturdy tripod housing the sampler, a powerful blower, and interconnected air tubes [256,257].

The instrument has been commonly used in measuring PM. For example, O'Connor et al. (2010) conducted a study on atmospheric connections of particulate matter emissions in marine and continental environments, employing the ChemVol Model 2400 [258]. Ghio et al. (2013) also utilised the instrument to investigate distinct responses of normal human bronchial epithelial cells cultured in medium and those permitted to differentiate at the air-liquid interface [259]. The PUF within the system, specifically the G5300 filter, captured fine and UFP, subsequently washed with water and methanol, and left to dry in aseptic conditions. Further procedures, such as prewetting the filter with 70 percent ethanol and extracting particulates through sonication, were conducted before lyophilisation. Mirowsky et al. (2013) employed the instrument to assess the comparative toxicity of fine and ultrafine particulate matter in vivo and in vitro in remote and urban areas of California [255,257,260–265]. Additionally, the ChemVol Model 2400 has been applied in various studies to ascertain chemical compositions and particle effects on health.

Harvard Impactors

The particulate matter FRM employs a gravimetric integrated approach in its methodology. An electrically driven collector facilitates the collection of outdoor air samples at a consistent volume flow rate. The atmospheric air specimen is drawn in at a rate of 16.67 L/min through a specially engineered entrance, designed to reject insects, flies, and environmental precipitation, while remaining unaffected by the direction and speed of the wind [266]. Particulates > 10 µm are effectively removed from the tested air by an impactor integrated into the intake [267]. Additionally, particulates > 2.5 µm undergo removal by a secondary inertial particulate splitter (WINS), positioned below the inlet. The remaining $PM_{2.5}$ is then gathered over a Teflon polytetrafluoroethylene (PTFE) collection foam (Figure 11).

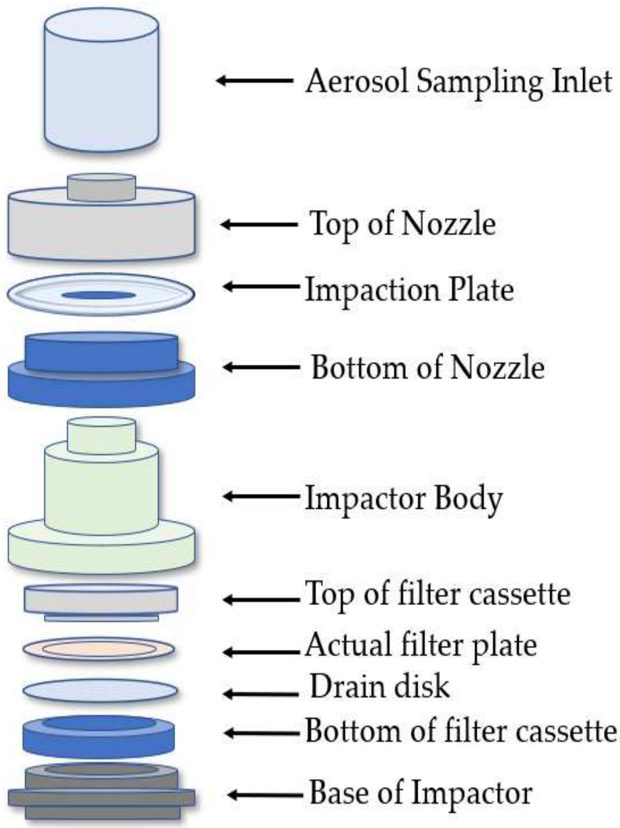

Figure 11. $PM_{2.5}$ Harvard Impactor collector.

Replacing the conventional substrate of the $PM_{2.5}$ Harvard Impactor with open pore PUF significantly improved particle collection efficiency, leading to reduced cut-off size and minimised particle bounce and re-entrainment. Kavouras and Koutrakis (2001) used the Harvard Impactor to investigate differences in the collecting efficiency curve between oil coated and PUF surfaces [268]. Findings indicated that variations in flow patterns, particularly under different Reynolds numbers, may be associated with these differences. The research further revealed that, among polyurethane foam and typical substrates, wider impaction sheet widths led to overall superior impactor efficiency. Additionally, the study observed that PUF substrates absorbed a greater fraction of excess kinetic energy from particles compared to conventional substrates, reducing particle bounce and re-entrainment. Furthermore, it can be said that overall impactor performance was better for larger impaction plate diameters for both PUF and conventional substrates. Stolez et al. employed the instrument to investigate the significance of exposure to particulate fractions of different sizes in total mortality and cardiovascular mortality. Similar studies [173,174] utilised Harvard Impactors for sampling $PM_{2.5}$, characterising them, and assessing their effects on human health.

4.2. Collection of Ultrafine Particulate Matter

Toxicological investigations involving UFPs often necessitate a substantial mass quantity of particulate [61,269]. The flow rate of samplers designed for UFP capture typically falls within the range of 9–30 L per minute [270,271], with most employing filters of dimensions 8 × 10 inches. However, Badran et al. (2020) used a 5-stage large-volume Cascade impactors with a flow rate of 1100 L per minute for the same propose [272], while Sotty et al. (2019) used large-volume impactor samplers with a flow rate of 400 L per minute [273].

UFP sampling instruments differ in their approach, utilising filtering at the primary phase to exclude larger particulates and secondary filtering at the final stage for capturing ultrafine particles. However, HCCI employ filters at each impaction stage, proving beneficial for toxicological investigations by efficiently capturing ultrafine particles in both internal and external environments [274,275]. Details of specific instruments for ultrafine particle collection are provided in the subsequent sections.

4.2.1. High-Volume Impactor Sampling Instruments

Staplex TFIA-2 High volume Sampler: The primary benefits of this sampler, compared to another low-volume sampler with a flow rate of 16.67 lpm, include reduced uncertainty in mass measurement, increased collection of particle mass, and shorter sampling duration [276]. Sotty et al. (2019) utilised the High-Volume Impactor Sampler (HVIS) for the sampling of fine-sized particulate fractions, with an aerodynamic diameter ranging from 0.18 μm to 2.5 μm ($PM_{0.18–2.5}$) through impaction, and ultrafine fraction particles with aerodynamic diameters less than 0.18 μm ($PM_{0.18}$) through filtering on polycarbonate A4-sized membranes [273]. Billet et al. (2018) investigated the significance of organic molecules in particulate matter toxicity [277]. A High Volume Staplex TFIA-2 model 5-stage plus backup HVCI was employed with a flow rate of 68 m^3/h (Figure 12); Billet et al. (2018) elucidated the process, emphasising the installation of impaction sheets without filters after excluding the first stage to capture particulates with the largest sizes. Impaction units were replaced every seven days, and two machines were used simultaneously to collect sufficient volumes of $PM_{0.3–2.5}$ for toxicological and physiochemical analyses.

Figure 12. Visual representation of Staplex TFIA-2 High volume Sampler [278].

Following collection, impaction sheets were dried for 48 h within a laminar air flow, and $PM_{0.3–2.5}$ was subsequently retrieved from collecting plates and stored at 20 °C. The dimensions of the Staplex TFIA-2 High volume Sampler are $8 - 1/2 \times 7 - 1/2 \times 7 - 1/2$ ($21.6 \times 19.1 \times 19.1$ cm) and carrying weight is 10 lbs. (4.5 kg). Borgie et al. (2015) used this instrument for the collection of $PM_{0.3–2.5}$ particles at a flow rate of 42 m^3/h [279]. Campbell et al. (2014) conducted experimental research investigating cellular responses associated with exposure to UFP using a functioning human neural tissue, a novel model system [280]. For UFP sampling, they utilised the (HVUP running at a flow rate of 400 L per minute with an 8 × 10-inch zeflour PTFE filter [280]. Li et al. (2017) mentioned the HVUP with a flow rate of 400 L per minute and Teflon filters of 8 × 10-inch size, exploring the link between oral consumption of ultrafine particulate matter and inflammatory bowel and atherosclerosis diseases [281]. Bliss et al. (2018) employed the HVUP instrument to investigate whether particulate matter-induced oxidative stresses and inflammatory reactions are interdependent in human white blood cells, also examining the impact of dosage and differentiating status on cellular function following a 24 h exposure to particulates using a normal line of white blood cells (THP-1) [282]. So, this instrument can even be used in the study which involved human primary white blood cells from eight non-smoker volunteers of varying ages to assess the impact of age on responsiveness [282].

4.2.2. Cascade Impactors

Dekati gravimetric impactor, 70 LPM: The DGI (Dekati Measurement Technologies) cascade impactor is designed with a high specimen rate of flow to monitor small concentration particulates effectively. Employing gravimetric calculations, it delineates the size mass distribution of particulates, especially those under 2.5 µm, into five distinct particle sizes [283]. Ruusunen et al. (2011) studied that this cascade impactor finds common applications in exhaust emission monitoring, ambient air investigations, and various shallow concentration operations where a rapid sampling rate of flow is essential [284]. DGI impactor captures size-differentiated particles on a 47 mm diameter substrate, facilitating subsequent chemical or gravimetric analysis [284]. The smallest particulate fraction is collected on a 70 mm diameter filter (Figure 13), the dimensions of the instrument are H110 mm × W130 mm.

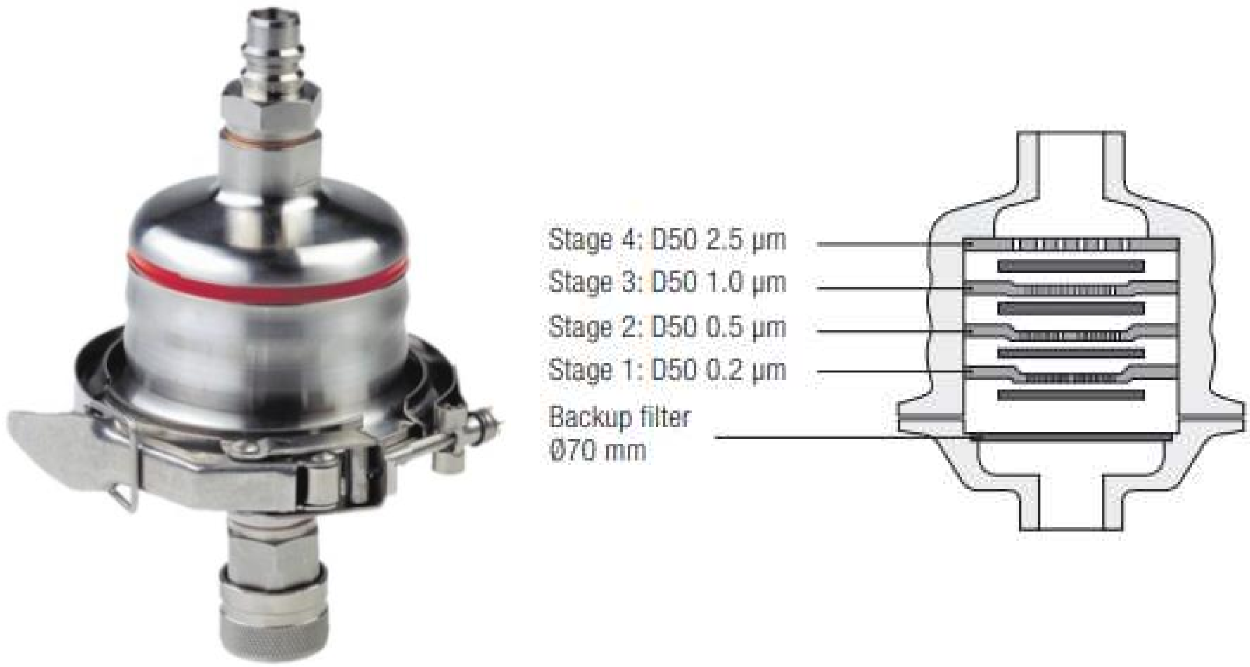

Figure 13. Visual representation of DGI (Dekati gravimetric impactor, 70 LPM) [285].

Ruusunen et al. (2011) utilised a combination of the Droplet Measurement Technologies (DGI) and a Porous Tube Diluter (PRD) for the purpose of particle collection [284]. They specified that the DGI was specifically engineered to isolate size-particulate samples from exhaust tailpipes, demonstrating a modest volume flow of 70 L per minute [284]. Due to its compact size, relative to the HVCI, it emerges as a favourable choice for the collection of substantial volumes of particle specimens in fieldwork, particularly for biochemical and toxicological investigations. Lamberg et al. (2011) extended this approach [286], utilising the DGI sampler coupled with PRD, maintaining the same settings as Ruusunen et al. (2011), with a flow rate of 70 L/min and a particle size fraction ranging from 0.2 µm to 2.5 µm, and the inclusion of an additional supporting filter for the 0.1 µm particle size [286].

The studies stamped the fact that DGI investigates particles generated in diverse combustion settings within household devices, correlating their findings with intrinsic chemical and physical properties of particulates [284,287,288]. Wang et al. (2015) [289] integrated the DGI with a low-pressure impactor (LPI) [290,291] to collect PM. In their experimental study, they explored the PM collecting properties of an electrostatic precipitator and investigated the dispersal of particulates in solid burning byproducts. Additionally, Seames and Wendt

(2000) utilised the DGI to collect $PM_{0.2}$, $PM_{0.5}$, PM_1, and $PM_{2.5}$, focusing on toxicology, element content, polycyclic aromatic hydrocarbons, and ions in particulate samples [291].

MOUDI (Micro-orifice uniform deposit impactor, 30 LPM): A diverse array of impactors has been conceived and employed in various aerosol collection studies since the advent of impactors around 1860 [292]. The Micro-Orifice Uniform Deposit Impactor (MOUDI) was meticulously designed with sample durations spanning several hours a day, primarily tailored for industrial applications in worksite environments [292]. The pivotal inclusion of a rotating impaction sheet and nozzle plates played a crucial role in MOUDI, ensuring a relatively uniform deposition on the impaction surface. Challenges, such as particle bouncing and deposition overload, prevalent in impactors with static impaction plates, were effectively mitigated through the dispersal of deposition [293] (Figure 14). The dimension of the instrument Model 120R and Model 125R are 80 × 510 mm (impactor) and 210 × 640 mm (cabinet).

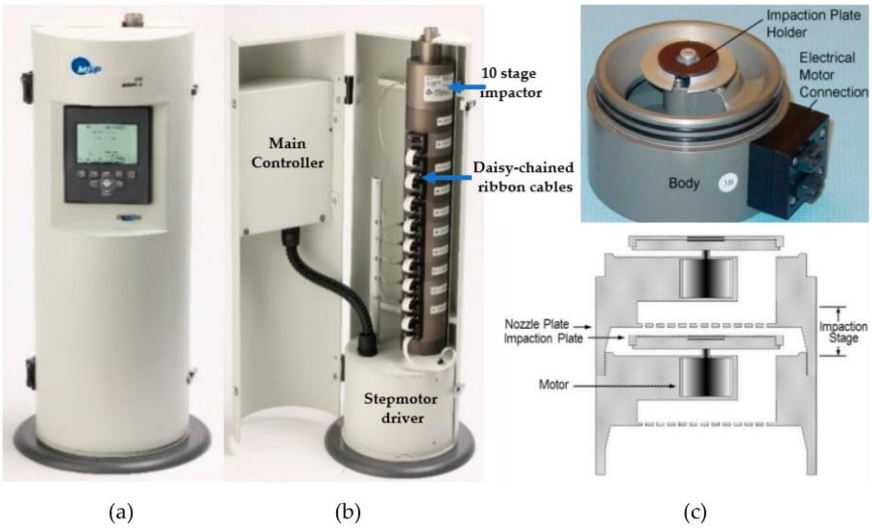

Figure 14. Visual representation of a MOUDI II Impactor Model. (**a**) View of Model 120R MOUDI II Impactor. (**b**) View of Model 120R MOUDI II Impactor parts of the instrument. (**c**) Motor with impactor stage, and its internal view [293].

Additionally, Marple et al. (2014) demonstrated the effectiveness of utilising the 120 MOUDI-II in prolonged PM sampling, showcasing its reliability and validity in continuous, stable collection over extended durations (approximately around 1 week) in both summer and winter conditions [293]. The enhanced capacity for extended collection allows operators to discern minor changes in size-segregated PM concentrations, potentially originating from nearby industrial sources. Allen et al. (2001) utilised the 10-stage MOUDI instrument in their study, resolving aerosol size fractions [294]. The incorporation of input and backup phases facilitates particulate capture in twelve particle sizes ranging from 0.066 µm to 19.5 µm, utilising PTFE filtering surfaces at a flow rate of 25.5 L/min. Researchers have corroborated and employed MOUDI for various applications, including aerosol particle size and mass distribution, as well as aerosol density [295–301].

Personal Cascade Impactor Sampler (PCIS): The Personal Cascade Impactor Sampler (PCIS) is a miniaturised cascade impactor equipped with four impaction stages and an after-filter [302]. Its functionality involves the separation of particles into distinct aerodynamic diameter ranges: less than 0.25, 0.25–0.5, 0.5–1.0, 1.0–2.5, and 2.5–10 µm. Operational at a flow rate of 9 LPM, the PCIS employs a highly efficient, battery-operated light pump, maintaining a pressure drop of 11 in H_2O (2.7 kPa) [302]. Characterisation of the PCIS involved the utilisation of PTFE (Teflon), quartz, and aluminium substrates. Validation experiments utilising monodisperse polystyrene latex (PSL) particles, as well as polydisperse ammonium sulphate and ammonium nitrate aerosols, confirmed the precision of the cutpoints [302]. Misra et al. (2002) conducted an investigative study identifying 2.5 cm

Teflon filters as the most effective impaction substrates due to their superior collection efficiency above the cutpoints of each stage, minimal collection of particles below the cutpoints (a common limitation with quartz substrates), and suitability for gravimetric analysis [302]. Particle loading assessments indicated that the PCIS stages could capture up to 3.16 and 0.7 mg of fine and coarse PM, respectively, without sacrificing collection efficiency due to particle bounce. Singh et al. (2003) conducted a comprehensive field and wind tunnel assessment of the instrument, a 4-stage miniaturised cascade impactor equipped with an after-filter (Figure 15a–d) [303]. The efficacy of the PCIS was further assessed through wind tunnel experiments conducted at wind velocities reaching 8 km/h. These investigations revealed that the particle sampling efficiency and separation properties of the PCIS remained unaffected by varying wind speeds, even for particles with aerodynamic diameters of up to 10 µm. The sampler's overall weight is approximately 150 g, rendering it manageable for experimentalists [303]. Particles ranging from 0.25 µm to 10 µm traverse rectangular nozzles and are subsequently captured on 25 mm substrate panels composed of quartz, aluminium, or Zefluor (pore size 0.5 µm). The after-filter, crafted from PTFE, Teflon (pore size of 2 µm), or quartz, with a diameter of 37 mm, collects particulates < 0.25 µm. The Personal Cascade Impactor Sampler is designed to affix to a subject's collar during inhalation, with the pump ingeniously attaching to the subject's buckle for real-world applicability.

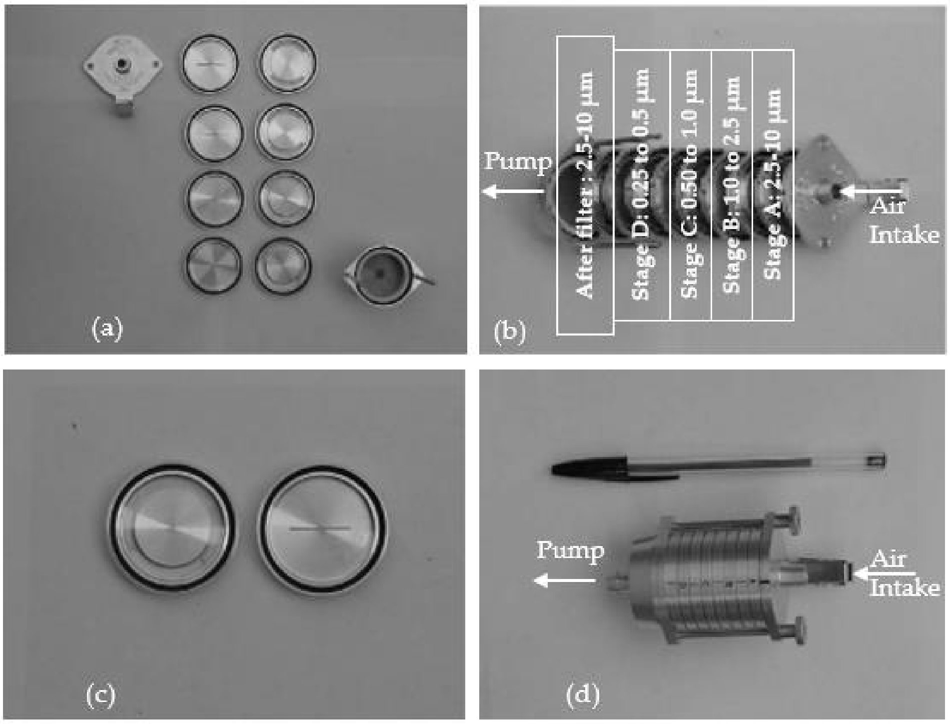

Figure 15. Visual representation of a Personal Cascade Impactor Sampler (PCIS); (**a**) Dismantled view of interior sections of PCIS (**b**) Schematic representation of the five interior sections of a PCIS, (**c**) Zoomed dismantled view of interior section, (**d**) Picture of PCIS unit, pen placed for perspective of size [303].

Chen et al. (2018) delved into some modifications of the Sioutas Personal Cascade Impactor Sampler (PCIS) concerning design alterations and a reduced flow rate [304]. They innovatively engineered a compact 10-stage sampler with a flow rate of 2 L/min, weighing merely 0.27 kgs and measuring 8.5 × 5 × 11.4 cm in dimensions. This device boasts cutpoints spanning from 60 nm to 9.6 µm. Chen et al. (2018) conducted further experimentation, demonstrating that, with the utilisation of a portable battery-driven pump, the top 8 stages, proficient in capturing particulates as small as approximately 170 nm in aerodynamic diameter, can be effectively utilised as discrete impactors [304].

Glass fibre and aluminium filters, conventional substrates, were employed to gauge the particulate collection efficiency of the impactor. The use of aluminium substrates aligns seamlessly with the established impactor concept. Consequently, the compact design of the impactor does not compromise efficacy, rendering it well suited for practical systems, where a low flow rate is deemed suitable for the bulk sampling of particulates. Moreover, PCIS finds diverse applications [213–220], including but not limited to pharmaceutical, epidemiological, occupational hygiene, and inhalation toxicology research.

5. Conclusions

The research summarised/reviewed the impact of fine and ultrafine particles on human health. An examination of five distinct sources of particulate matter is undertaken, followed by a discussion of their health implications. Human exposure to vehicular emissions is associated with adverse effects such as stroke, all-cause mortality, heart failure, cardiovascular and respiratory disorders, pulmonary inflammation, cytotoxicity, and cardiotoxicity. Similarly, exposure to particulate matter exhaust from coal-driven power plants is linked to all-cause, respiratory, and cardiovascular morbidity, lung cancer deaths, pneumonia, and cardiac mortality. Diesel engine particulate matter exposure may lead to infection susceptibility, atopy, allergic inflammation in the throat and nose, lung functioning disorders (including lung cancer), changes in heart functioning, oesophageal cancer, and respiratory mortality. Furthermore, human exposure to particulate matter exhaust from household wood burning may result in respiratory exacerbation, mortality, lung functioning disorders, and inflammation. Inhaling atmospheric dust particles may cause lung infection and inflammation, along with all-cause, respiratory, and cardiac mortality. This review concludes that the deposition of ultrafine particles in various lung regions through diffusion depends on particle size. UFPs with a size of 0.001 μm primarily deposit (approximately 90%) in the nasal, pharyngeal, laryngeal regions, with around 20% and 0% deposition in the alveolar and tracheobronchial region. Particles sized 0.01 μm exhibit the highest deposition efficiency in the alveolar region and moderate deposition in nasopharyngeal and tracheobronchial regions. This review adds to the research of deposition of particulate matter in the respiratory tract can initiate a cascade of inflammatory responses, oxidative stress, and cellular damage, contributing to the observed health effects. The nasopharyngeal deposition of smaller particles (0.001 μm) serves as a gateway for potential adverse health outcomes, emphasising the significance of understanding regional deposition dynamics.

To comprehensively assess the health risks associated with particulate matter exposure, the research delves into the methods used for measurement. Accurate measurement of both particle concentration and size distribution is imperative for understanding the nature and extent of exposure. Robust methodologies, such as gravimetry, impactors, and cascade impactors, provide nuanced insights into particulate matter characteristics. Understanding these measurement techniques enhances our ability to pinpoint pollution sources, assess air quality, and implement targeted interventions. In conclusion, the intricate relationship between particulate matter characteristics, deposition patterns, and associated health outcomes underscores the multifaceted nature of this environmental health concern. By merging epidemiological observations with advanced measurement techniques, we gain a comprehensive understanding of the diverse factors influencing particulate matter-induced health effects. This knowledge is pivotal for formulating evidence-based policies, designing effective mitigation strategies, and safeguarding public health in the face of ongoing environmental challenges.

Furthermore, the current investigation delves into an exhaustive examination of the collection methodologies pertaining to fine and ultrafine particles, offering a comprehensive review of instruments employed in their retrieval. Also, this comprehensive examination of environmental research instruments has provided an in-depth analysis of various high-volume cascade impactors, and cascade impactor models, such as ChemVol 2400 and Staplex 236. The intricate mechanisms of these instruments, including the role of PUF filters, calibration procedures, and their application in diverse studies, ranging from atmospheric linkages to assessing particulate matter toxicity, were thoroughly scrutinised. The interplay of technical components, such as rain caps, tripods, and blowers, in the functioning of ChemVol 2400 was elucidated, emphasising their significance in maintaining intended flow rates.

Furthermore, the evaluation extended to instruments like the particulate matter FRM, Harvard Impactors, and high-volume ultrafine particulate samplers, exploring their roles in investigating genotoxicity, metabolic disruptions, and epidemiological connections. The detailed examination of DGI impactors and MOUDI highlighted their prowess in gravimetric particulate size mass distribution and continuous, stable collection over extended durations. This technical survey underscores the critical importance of these instruments in advancing pharmacological analyses of fine and ultrafine particulates, emphasising their increased toxicity and the inherent challenges in obtaining substantial sample masses for comprehensive investigations. This analytical review serves as a valuable guide for researchers in selecting precise methodologies for their nuanced studies on the environmental and health impacts of particulate matter.

6. Gaps in Knowledge

Based on the insights gained from this work, it is imperative to identify the gaps in knowledge that could further advance research in this field. One such recommendation is to explore the long-term health effects of exposure to particulate matter, especially focusing on vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions. Additionally, there is a need for more studies investigating the synergistic effects of particulate matter with other environmental pollutants, such as nitrogen oxides and volatile organic compounds. Furthermore, the impacts of emerging sources of particulate matter, such as microplastics, on human health remain poorly understood and warrant thorough investigation. By addressing these gaps in knowledge, researchers can continue to deepen the understanding of the complex relationship between particulate matter exposure and human health, ultimately informing evidence-based policies and interventions to mitigate the adverse effects of air pollution on public health.

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