Geoscience Frontiers xxx (2021) xxx

Contents lists available at ScienceDirect

Geoscience Frontiers

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

Research paper

Sources, characteristics, toxicity, and control of ultrafine particles: An overview

Andrea L. Moreno-Ríos [a,*], Lesly P. Tejeda-Benítez [b], Ciro F. Bustillo-Lecompte [c]

[a] Department of Civil and Environmental, Universidad de la Costa, CUC, Calle 58 # 55–66, Barranquilla, Atlántico, Colombia
[b] Research Group in Biomedical, Toxicological and Environmental Sciences (Biotoxam), University of Cartagena, Campus of Zaragocilla, Cartagena, Colombia
[c] School of Occupational and Public Health, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada

ARTICLE INFO

Article history:
Received 8 October 2020
Received in revised form 4 January 2021
Accepted 14 January 2021
Available online xxxx

Keywords:
Particulate matter
Ultrafine particles
Air pollution
Toxicity
Measurement methodologies

ABSTRACT

Air pollution by particulate matter (PM) is one of the main threats to human health, particularly in large cities where pollution levels are continually exceeded. According to their source of emission, geography, and local meteorology, the pollutant particles vary in size and composition. These particles are conditioned to the aerodynamic diameter and thus classified as coarse (2.5–10 μm), fine (0.1–2.5 μm), and ultrafine (<0.1 μm), where the degree of toxicity becomes greater for smaller particles. These particles can get into the lungs and translocate into vital organs due to their size, causing significant human health consequences. Besides, PM pollutants have been linked to respiratory conditions, genotoxic, mutagenic, and carcinogenic activity in human beings. This paper presents an overview of emission sources, physicochemical characteristics, collection and measurement methodologies, toxicity, and existing control mechanisms for ultrafine particles (UFPs) in the last fifteen years.

1. Introduction

Air pollution is one of the most studied environmental problems worldwide since it generates a continuous threat to people's health and quality of life. Particulate matter (PM) is among the primary air pollutants, and it is made up of a complex mixture of chemical and biological components (Garcia et al., 2014; Martinello et al., 2014; Schneider et al., 2015, 2016; Ramírez et al., 2019; Rojas et al., 2019; Silva et al., 2020a, 2020b; Zamberland et al., 2020). Depending on the aerodynamic diameter, particles are divided into coarse, fine, and ultrafine, ranging from nanometers (nm) to microns (μm), being the PM_{10} particles with an aerodynamic diameter between 2500 nm and 10000 nm, $PM_{2.5}$ particles between 100 nm and 2500 nm, and $PM_{0.1}$ particles less than 100 nm (WHO, 2006; Jeong et al., 2017; Clifford et al., 2018; Rizza et al., 2019). More specifically, it has been recognized that particles with a size smaller than 300 nm are considered as atmospheric nanoparticles (Kumar et al., 2016), and even smaller particle sizes (<100 nm), i.e. $PM_{0.1}$, are also considered as such (Dall'Osto et al., 2011; Da et al., 2019; de Jesus et al., 2019).

Ultrafine particles (UFPs) are produced by dynamic formation processes such as nucleation, condensation, and coagulation from compounds in the gas phase (León-Mejía et al., 2016, 2018; Ramírez et al., 2020). Nucleation frequently occurs in forested areas due to the emission of biogenic volatile organic compounds (VOCs) (Ehn et al., 2014). During condensation, gaseous molecules are transferred into nucleation mode particles or an existing particle (Seigneur, 2019). During coagulation, particle collisions can occur, leading to agglomeration into a single particle from two original particles. New nucleated UFPs coagulate readily with other particles, causing the deposition of UFPs (Zhao et al., 2015; Kwon et al., 2020). These UFPs processes are different from those in larger particles because changes in size, shape, surface area, volume, and number can occur at higher speeds than in larger particles (Kumar et al., 2016, 2018). After their formation, UFPs can remain suspended in the air for a longer time than larger particles (Abdel-Shafy and Mansour, 2016) and are later removed by dry and wet deposition (Kumar et al., 2011; Muñoz-Salazar et al., 2020).

Due to their size and large specific surface area, UFPs can be easily transported through the respiratory system penetrating the pulmonary alveoli (Clifford et al., 2018; Buzea and Pacheco, 2019). Thus, leading to pulmonary deposition (Guo et al., 2019) and systemic translocation (Allen et al., 2017; Bhargava et al., 2018; Clifford et al., 2018). Some hypotheses suggest that UFPs may have a higher health impact than larger particles (Da et al., 2019). However, there is still a short number of studies regarding long-term exposure to confirm such hypotheses and

* Corresponding author.
E-mail addresses: amoreno16@cuc.edu.co (A.L. Moreno-Ríos), ltejedab@unicartagena.edu.co (L.P. Tejeda-Benítez), ciro.lecompte@ryerson.ca (C.F. Bustillo-Lecompte).

https://doi.org/10.1016/j.gsf.2021.101147

Please cite this article as: A.L. Moreno-Ríos, L.P. Tejeda-Benítez and C.F. Bustillo-Lecompte, Sources, characteristics, toxicity, and control of ultrafine particles: An overview, Geoscience Frontiers, https://doi.org/10.1016/j.gsf.2021.101147

explain the biological mechanism through which these particles affect human health.

When talking about number and surface, fine ($PM_{2.5}$) and ultrafine ($PM_{0.1}$) particles are the most toxic airborne particles (Xiao et al., 2016; Soppa et al., 2019). Several studies have documented the relationship between the exposure to these particles and the morbidity and mortality of respiratory (Gao and Sang, 2020; Nho, 2020) and cardiovascular diseases (Xiao et al., 2016; Bourdrel et al., 2017; Yang et al., 2017b; Liu et al., 2018; Møller et al., 2020).

Indeed, there is strong evidence that certain diseases such as asthma, chronic obstructive pulmonary disease (COPD), pulmonary fibrosis, neurodegenerative diseases (Heusinkveld et al., 2016; Wei et al., 2017), cancer (Gao and Sang, 2020), and type 2 diabetes are related to the exposure of particles that are smaller than 2.5 μm (Chen et al., 2016). Likewise, it is proposed that chemical compounds such as polycyclic aromatic hydrocarbons (PAHs), N-PAHs (Zhang et al., 2016, 2020; Agudelo-Castañeda et al., 2017), potentially toxic elements (colloquially named heavy metals) (Pourret and Hursthouse, 2019), sulphur and nitrogen oxides (Santibáñez-Andrade et al., 2017; Billet et al., 2018), commonly found in fine particles, can lead to genotoxic, mutagenic, and carcinogenic activity (Santibáñez-Andrade et al., 2017; Shukla et al., 2019).

Although there is plenty of information regarding PM's toxicological effects, few studies include UFPs in their toxicity analysis. This gap in the literature is attributable to technical difficulties in measuring the concentration of UFPs and estimating the exposure of the included population (Silva et al., 2012a; De Vallejuelo et al., 2017; Saikia et al., 2018). In this way, this paper presents an overview of the state of the art of research on atmospheric UFPs. Among the topics discussed are the primary emission sources, their main characteristics, collection and measurement methodologies, toxicity, and controlling mechanisms available to eliminate and prevent contamination.

1.1. Pollution sources of ultrafine particles

The pollutants that make up the particles vary in size and composition according to the sources of contamination. Fig. 1 shows the primary emission sources, which may be either natural or anthropogenic (Jones and Harrison, 2016; Mishra et al., 2016; Abramesko and Tartakovsky, 2017; de Oliveira Galvão et al., 2018). Indeed, PM is emitted directly into the atmosphere as primary particles or formed in the atmosphere from the transformation of gaseous precursors as secondary particles (Kumar et al., 2016) and photochemical generation of new particles (Ma and Birmili, 2015; Chu et al., 2019).

Natural sources of UFPs include forest fires, volcanic eruptions, marine aerosols, local minerals and runoff (Dalmora et al., 2016; Dias et al., 2014; Islam et al., 2019; Kronbauer et al., 2013). However, UFPs mainly originate from anthropogenic sources such as combustion of gas, coal or hydrocarbons, biomass burning (i.e. agricultural burning, forest fires and waste disposal), vehicular traffic (Abramesko and Tartakovsky, 2017) and industrial emissions (Keuken et al., 2015). Other sources are tire wear and tear from car brakes, air traffic (Keuken et al., 2015; Kecorius et al., 2016; Habre et al., 2018; Stacey, 2019; Møller et al., 2020), seaport, maritime transportation (Agudelo-Castañeda et al., 2019), construction, demolition, restoration and concrete processing (Azarmi and Kumar, 2016; Azarmi et al., 2016; Kumar et al., 2016), domestic wood stoves (Marabini et al., 2017), outdoor burning, kitchen (Chen et al., 2017), and cigarette smoke (Goel and Kumar, 2015).

2. Characteristics of ultrafine atmospheric particles

2.1. Physicochemical properties of ultrafine particles

PMs are significant air pollutants as they undergo high variability in terms of their physicochemical and morphological properties, concentration levels, and composition, which vary with the season, climate, space and source; making it challenging to analyze its toxic components (Kelly and Fussell, 2012; Castro-Rodriguez et al., 2016; Lee et al., 2017; Saikia et al., 2018; Buzea and Pacheco, 2019). UFPs are PMs with an aerodynamic diameter of less than 0.1 μm. UFPs are typically described in terms of surface area per particle, mass or particle number (PN), or concentration of either of those per volume (Kwon et al., 2020). Fig. 2 shows the main properties of UFPs and the factors that affect them.

Having a diameter of less than 0.1 μm allows UFPs to remain suspended in the air for a more extended time than larger particles (Kelly and Fussell, 2012). It has been found that the residence time, dispersion, transport, and emission processes of UFPs in the air are affected by environmental conditions (Oliveira et al., 2017, 2019a, 2019b). These include the meteorological factors of the geographical area such as wind direction and speed, temperature variations, relative humidity, mixing height, precipitation and solar radiation, orography, and the physicochemical processes that are carried out in the atmosphere, which also may vary depending on the location (Schneider et al., 2015; Kumar et al., 2016; Kumar et al., 2018).

UFPs are unstable and become larger particles through coagulation and condensation. These particles are mainly made up of sulphates, nitrates, trace metals, elemental and organic carbon, and adsorbed volatile and semivolatile organic compounds (Simkhovich et al., 2008).

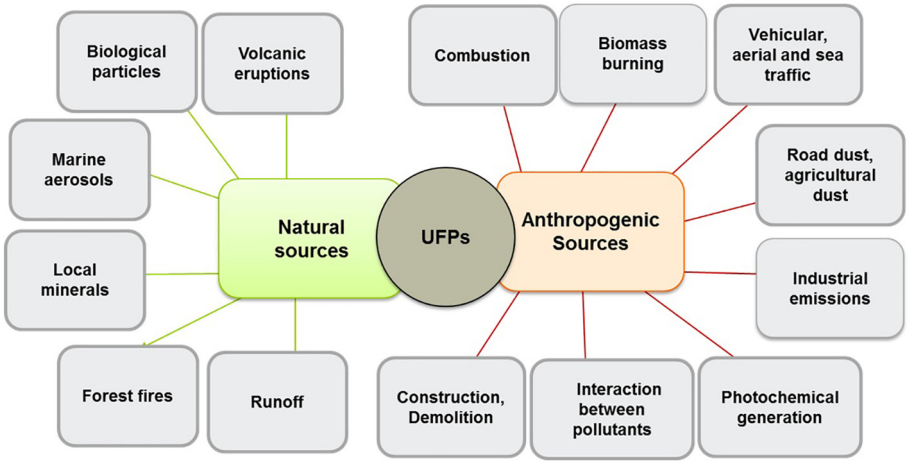

Fig. 1. Ultrafine particle emission sources.

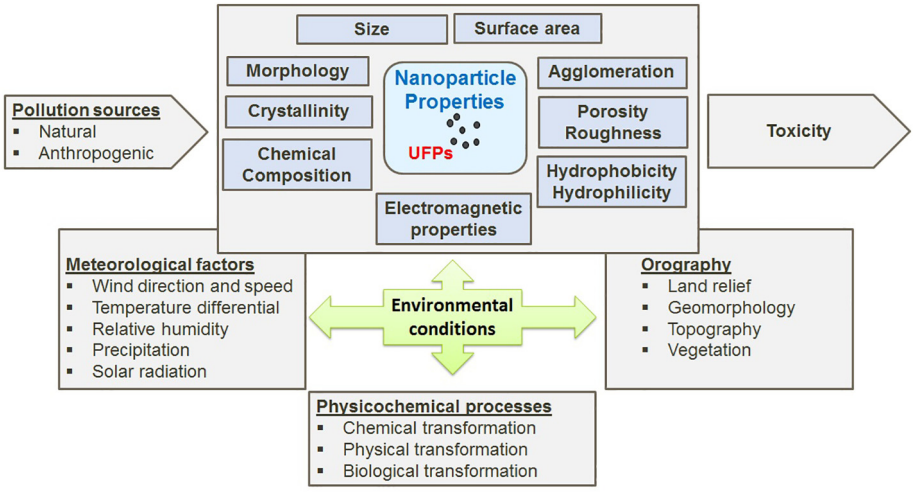

Fig. 2. Properties of UFPs and the factors that affect them.

However, the number of UFPs per unit volume is greater compared to the larger particles; this increases the available surface area increasing, in turn, the adsorption of other polluting elements such as organic gases, potentially toxic elements, forming larger coated or agglomerated particles, and with greater toxicity (Chen et al., 2016).

Following the above, the physicochemical properties of UFPs depend on the nature of the substances that form its nucleus and the different chemical components that make up their surfaces. For instance, the UFPs composition, when emitted by wood combustion, can be augmented or modified depending on the by-product combustion, such as PAHs, ions, potentially toxic elements, and other oxidizing components present in the air (Civeira et al., 2016; Oliveira et al., 2019a, 2019b). These particles may also undergo chemical modifications by exposure to UV-A and UV-B radiation (Marabini et al., 2017). It is shown that environmental UFPs are highly enriched in transition metals and easily oxidized organic chemicals, which harbour potent toxic properties and high oxidant power (Allen et al., 2017).

When combustion gases originate from motor vehicles, the emitted particles' characteristics hinge on the fuel's composition, the lubricants used, the thermodynamic conditions associated, ignition technology, and the number of vehicles running. For that reason, it is essential to perform emission inventories in big cities. For example, heavy vehicle emissions tend to be very high compared to smaller ones related to the type of fuel used (Sydbom et al., 2001). The particles emitted by diesel engine vehicles are mainly in the range of 20–130 nm, whereas gasoline is 40–80 nm (Agudelo-Castañeda et al., 2019).

2.2. Chemical composition of UFPs

The chemical composition of UFPs in different environments is not widely studied (AQEG, 2017). In the atmosphere, UFPs are derived from a considerable number of sources. To date, relatively little work has been devoted to breaking down the size distribution into source-related components due to the difficulty of changing size distributions from both particle evaporation and growth, as well as the influence of atmospheric nucleation processes that lead to the formation of new particles (Kumar et al., 2014). UFPs are mainly composed of organic compounds, elemental carbon, trace metal oxides, sulphates, and nitrate ions (Lü et al., 2012, 2016). Most of the mass of $PM_{0.1}$ is typically composed of carbonaceous material with small contributions of inorganic ions, thus confirming the dominant combustion sources (HEI, 2013). Table 1 shows the contaminants present in the particulate material according to their emission source.

Table 1
Emission source vs composition in ultrafine particles.

Emission source	Composition	References
Coal combustion	Al, As, Ba, C, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, Rh, S, Se, Si, Ti, V, Zn, PAHs	Bzdek et al. (2012), Lü et al. (2016), Oliveira et al. (2017), Abbas et al. (2018), Saikia et al. (2018), Thurston et al. (2011)
Biomass burning	Organic Carbon, PAHs, Metals	Bzdek et al. (2012), Abbas et al. (2018), De Oliveira Galvão et al. (2018), Badran et al. (2020)
Fossil fuel combustion	BC, Organic Carbon, PAHs	Bzdek et al. (2012), Louis et al. (2016), Abbas et al. (2018), Paunescu et al. (2019)
Vehicular traffic	Ag, Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Pd, Pt, Rh, Rb, Sb, Se, Sr y Te, Ti, U, V, Zn, PAHs, BC	Srimuruganandam and Shiva Nagendra (2011), Hofman et al. (2018), Liati et al. (2018), Guo et al. (2019), Gao et al. (2020)
Industrial emissions	As, Cd, Cu, Co, Cr, Pb, Zn, Ni, Zn	Fernández-Camacho et al. (2012), González et al. (2017)

Metal sulphates and nitrates can exist as pure solid or aqueous particles or as a surface layer on other solids, such as ash or carbon particles (Cutruneo et al., 2014; Silva et al., 2020a, 2020b). Likewise, sulphate particles can be covered by toxic components such as transition metals or organic compounds (Kelly and Fussell, 2012). The elemental and organic carbon particles come mainly from combustion processes and contain up to 80% to 90% of UFPs, black carbon (BC), and organic carbon. These particles can serve as nuclei in which other chemical species are absorbed (Kelly and Fussell, 2012).

BC is a primary aerosol product of incomplete combustion of fossil fuels or biomass from anthropogenic activities such as transportation, industrialization, and burning solid waste (Silva et al., 2012a, 2012b, 2020a, 2020b; Ribeiro et al., 2013a, 2013b; Ribeiro and Flores, 2020; Gasparotto et al., 2018, 2019; Gasparotto and Da Boit, 2020). It is generally used as an indicator of the type of fuel used and the type of combustion because its physical properties and concentration levels change with fuel type (Jeong et al., 2017). Due to its physicochemical properties, BC can adsorb primary and secondary pollutants and serve as a substrate for various chemical processes, whereas at an environmental level, it can reduce visibility and hinder plant growth by adhering to its surface (Keuken et al., 2015; Kumar et al., 2018).

Among the organic constituents of PM, PAHs are of great interest. They are mainly introduced into the atmosphere during the combustion process and can give rise to atmospheric physicochemical reactions that

result in the formation of derivatives of PAHs such as N-PAHs and O-PAHs. The concentrations of these compounds in airborne particles can be very low, but their toxic effects are often considered higher than those of their parent compounds (Zhang et al., 2016; Abbas et al., 2018; Song et al., 2019).

The primary precursor gases for secondary UFPs are biogenic volatile organic compounds (VOCs) such as alpha-pinene, aromatic VOCs such as two to four-ring PAHs, NOx, and SO_2. The formation of new particles is also favoured by photochemical processes mediated by solar radiation, the low concentration of pre-existing aerosols, and low relative humidity (Muñoz-Salazar et al., 2020).

On the other hand, there is a wide range of known sources that contribute to increased levels of metals such as Na, Ca, K, Al, Fe, Se, Ti, and potentially toxic elements (Hg, Pb, Cd, Cr, As) in the finer PM fractions (Sanderson et al., 2014). The concentrations of metals with a lower atomic mass (As, Cd, Zn) decrease with particle size, while those with higher atomic mass (Co, Cr, Fe, Sb, Sc, Sm, Th, Eu, Yb) increase their concentration in relation to the diameter of the particles. Most volatile compounds emitted in gaseous forms at high temperatures nucleate or condense during cooling (Sanderson et al., 2014), while the less volatile elements remain in their solid phase (Buonanno et al., 2011).

Among the sources of emission, heavy industries are considered one of the largest anthropogenic sources of trace metals (Fernández-Camacho et al., 2012; Zhou et al., 2014; González et al., 2017), even traffic emissions can be considered essential sources of PM and metals in urban atmospheres (Fernández-Camacho et al., 2012; Abramesko and Tartakovsky, 2017).

3. Toxicity of ultrafine atmospheric particles

Effects of particulate matter cover a wide range of problems. It is shown that in urban environments, PM can alter the climate, the biogeochemical cycles, the chemistry of the atmosphere, and adversely disturb public health (Koçak et al., 2007). Adverse biological effects associated with PM include oxidative damage (Miller et al., 2012; Wei et al., 2017; Bliss et al., 2018; Shukla et al., 2019; Gao et al., 2020), cytotoxicity (Buzea et al., 2007; Sharma et al., 2018), and mutagenicity followed by increased morbidity and mortality (Agudelo-Castañeda et al., 2017; Ohlwein et al., 2019). Likewise, this contaminant is highly related to diseases such as cancer (Gao and Sang, 2020) and cardiopulmonary mortality (Agudelo-Castañeda et al., 2017; Maji et al., 2017; Liu et al., 2018; Ohlwein et al., 2019).

Some authors have considered that the particles' toxicity depends mainly on their composition (Kelly and Fussell, 2012). However, as previously mentioned, both the chemical composition and the particles' size are highly dependent on geographic location, meteorological conditions, and emission sources, making the identification and prediction of their toxic effects complex.

Fig. 3 summarizes the main effect and mechanisms of toxicity associated with exposure to UFPs. Between mechanisms associated with exposure to UFPs and their components (BC, metals, ions, organic compounds, among others), oxidative stress can lead to inflammatory processes and unchain cardiovascular diseases, carcinogenicity, epigenetics, genotoxicity, mutagenicity, neurotoxicity, and even teratogenicity (Miller et al., 2012; Wei et al., 2017; Bliss et al., 2018; Shukla et al., 2019; Cervellati et al., 2020; Gao et al., 2020). The toxicokinetics and mechanisms followed by UFPs and associated pollutants are presented below.

3.1. Toxicokinetics of ultrafine particles

In order to get a better understanding of the toxicology of UFPs, the processes of absorption, distribution, metabolism and excretion, and the toxic consequences of the presence of UFPs in the human body are described below.

The inhalation pathway is the main route to UFPs exposure, and hence, causes the most significant effects on human health; whereas, dermal, ocular, and nasal mucosal contact constitute forms of lower exposure (Chen et al., 2016; Yang et al., 2017a, 2017b). The deposition sites in the respiratory tract are determined by the particles' characteristics, including size, shape, surface charge, chemical composition, morphological and physiological parameters of the exposed individual's respiratory tract system (Kelly and Fussell, 2012; Sharma et al., 2018; Martins et al., 2021). The latter can vary considerably according to various factors, such as age, physical activity, respiratory rate, and health status. The subject's age is essential because the respiratory system's morphology and dimensions change with age (Da et al., 2019).

Inhaled airborne UFPs initially enter the nasal cavity and then go deeper into the lower airways, including the trachea, bronchi, and pulmonary alveolus. A mucus layer constitutes the initial defence line in the respiratory tract's membranes, which retains the larger particles (Chen et al., 2016). The smaller the size of the particles, the deeper they can enter into the respiratory system. In this way, particles up to 100 μm will be deposited in the nasopharynx, those of 10 μm will be

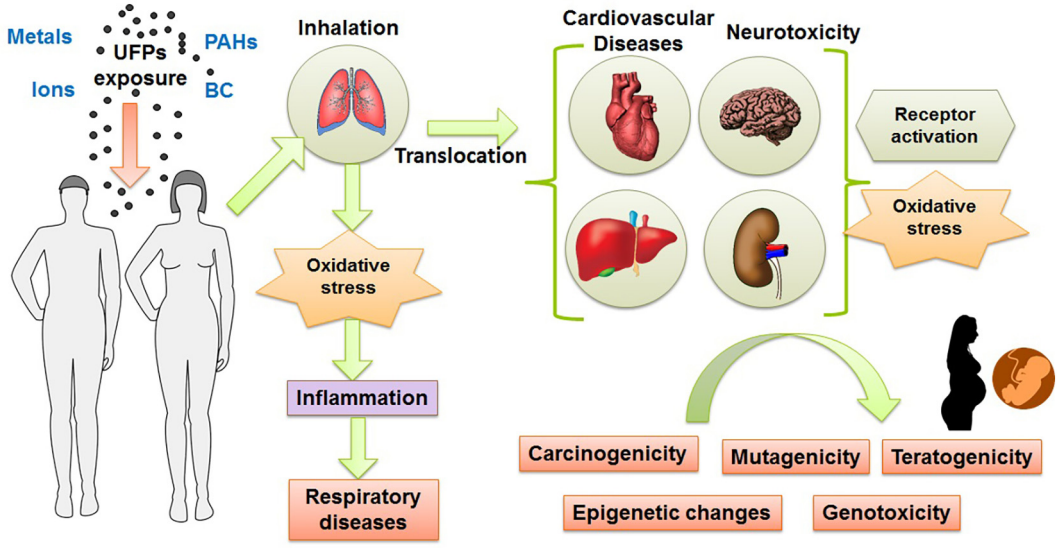

Fig. 3. Toxicological effects from exposure to UFPs.

deposited mainly in the primary bronchi, and those of sizes smaller than 2.5 μm will penetrate the alveoli and terminal bronchioles (Kelly and Fussell, 2012). UFPs can penetrate deeper into the lung (Cheng et al., 2020; Nho, 2020) since the pulmonary alveoli and human cells have diameters of 200 μm and 8 μm, respectively, higher than those of the UFPs (Buzea and Pacheco, 2019).

The lungs of adult humans have about 480 million alveoli. These, in turn, are composed of type I and type II alveolar epithelial cells (pneumocytes) and thin blood capillaries. Non-ciliated bronchiolar epithelial cells and lung immune cells are also present, eliminating microorganisms and inhaled particles (Nho, 2020). Macrophages are critical regulators in the immune response. When fine and ultrafine particles enter the respiratory system, macrophages are activated to eliminate them by phagocytosis. Simultaneously, they initiate the expression of various cytokines (IL-1 and TNF-α) and chemotoxins that will promote the inflammatory response to neutralize the strange agent. These molecules can also stimulate epithelial and endothelial cells, producing proinflammatory mediators, and increasing the number of leukocytes, primarily neutrophils (Nho, 2020).

Some authors have suggested that episodes of high concentration of particles could affect the phagocytic capacity mediated by macrophages and mucociliary clearance, leading to inflammatory processes. UFPs can also damage airway epithelial cells and macrophages by producing reactive oxygen species (ROS) from redox reactions in the mitochondria (Habre et al., 2018). In this way, particles not eliminated by the alveolar macrophages can promote damage to the lungs and other organs (Donaldson et al., 2001; Lundborg et al., 2001; Oberdörster et al., 2002; Allen et al., 2017; Buzea and Pacheco, 2019; Da et al., 2019). These damages can be associated with the presence of chemical components in the particles, such as metals, BC, and PAHs that can contribute to the increase in ROS formation and consequently in the inflammatory processes (Klaassen, 2013; Zhang et al., 2016; Crobeddu et al., 2017; Sharma et al., 2018; Cervellati et al., 2020; Gao et al., 2020; Li et al., 2020).

The inhaled particles deposited in the respiratory tract can be translocated into the bloodstream and subsequently to the body's different organs (Buzea and Pacheco, 2019; Da et al., 2019). They can also be translocated through epithelial barriers and along the olfactory and sensory neuronal pathways to subsequently reach other organs, including the brain (Chen et al., 2016). This translocation may vary depending on the size, chemical composition, surface charge, and aggregation of the particles (Sharma et al., 2018; Martins et al., 2021). Once in the circulation, a part of these particles can be translocated through the blood-brain barrier to the brain parenchyma (Heusinkveld et al., 2016). The particles can pass through the blood-brain barrier intact in several ways, for instance, passive crossing by simple diffusion (passive lipophilic materials) or through a protein-mediated energy-dependent active transport carrier or receptors (Heusinkveld et al., 2016).

After the transport of the particles and their translocation to the different organs takes place, the pollutants present in the particles can accumulate selectively in adipose tissues of the body and/or interact with other substances, which can increase their toxicity (Timbrell, 2009; Klaassen, 2013; Zhang et al., 2019). This will depend on the chemical characteristics, reactivity, and affinity of the chemical substance. For instance, organic compounds are hydrophobic and tend to accumulate in the body's organs and lipid tissues, contributing to fatty liver diseases (Rengarajan et al., 2015; Abdel-Shafy and Mansour, 2016; Wahlang et al., 2019).

3.2. Mechanisms of UPFs toxicity

As previously mentioned, PM exposure effects depend on particle size, chemical composition, morphology, crystallinity, surface area, roughness, porosity, agglomeration, hydrophobicity, hydrophilicity, and electromagnetism. These characteristics depend on the place of origin and source of contamination (Kelly and Fussell, 2012; Klaassen, 2013; Sharma et al., 2018; Buzea and Pacheco, 2019; Martins et al., 2021). In this way, contaminants found in UFPs include inorganic ions, trace metals, elemental carbon, carbonaceous organic matter, water, among others (Yadav et al., 2018; Song et al., 2019; Chen et al., 2020).

Many studies have confirmed that potentially toxic elements within PM were harmful to human health (de Kok et al., 2006; Saikia et al., 2018; Zhang et al., 2018; Briffa et al., 2020). Transition metals, such as Cr, As, Cd, and Ni, have been listed as carcinogenic to humans (Chen et al., 2019). Metals are known for their relationship with the generation of ROS, including hydroxyl radicals (Briffa et al., 2020; Gao et al., 2020), which can have unwanted effects, such as lipid peroxidation, proteins and DNA damage, cell death (apoptosis), and genotoxicity (Miller et al., 2012; Zhang et al., 2018b; Bhargava et al., 2019; Badran et al., 2020; Platel et al., 2020).

Oxidative stress and inflammation are associated with many disorders such as cardiovascular diseases (Simkhovich et al., 2008; Jantzen et al., 2016; Bliss et al., 2018), neurological diseases (Wei et al., 2017), and cancer (Buzea and Pacheco, 2019; Gao and Sang, 2020). Both fine particles and UFPs contain higher concentrations of toxic metals, such as Pb, Cd, and Ni (Liu et al., 2018); this is partly because these particles have a higher surface area and volumetric ratio, which gives them a more significant potential to transport toxic compounds compared with coarse particles (Burtscher and Schüepp, 2012; Chen et al., 2016).

Concerning the cardiovascular effects generated by UFPs, Miller et al. (2012) proposed three hypotheses that explain how inhaled particles can cause cardiovascular effects: (i) particles induce an inflammatory response in the lungs, which leads to the release of cytokines and other third party particles in the systemic circulation, (ii) UFPs can be translocated through the alveolar wall and interact directly with the cardiovascular system, and (iii) particles can activate the autonomous nervous system through sensory receptors on the alveolar surface, altering the autonomic nervous system activity that leads to indirect alterations of cardiovascular function. Other pathways may also undergo some activities, such as the translocation and stimulation of sensory receptors in the upper airways and nasal epithelium, the translocation through the gastrointestinal tract after mucociliary clearance, the accumulation of constituents of PM, the amplification of the inflammatory pathways in adipose tissue, and the effects on the central nervous system (CNS) that can regulate the endocrine system (Miller et al., 2012).

On the other hand, the organic fraction of particles contains hundreds of different compounds, including VOCs, BC, PAHs, and N-PAHs (Kim et al., 2013; Badran et al., 2020). The latter have toxic, mutagenic, genotoxic, and carcinogenic properties (Kim et al., 2013; Topinka et al., 2013; Agudelo-Castañeda et al., 2017; Landkocz et al., 2017; Santibáñez-Andrade et al., 2017; Feng et al., 2019). Likewise, they are highly soluble in lipids, so they are easily absorbed in fatty tissues and lipophilic systems in the human body (Abdel-Shafy and Mansour, 2016; Abbas et al., 2018).

PM's genotoxic and carcinogenic effects have been found to be related to the organic fraction, including PAHs and their derivatives, which are part of the organic fraction. These compounds have been mainly related to the ultrafine fraction because they have a greater specific area than larger particulate material (Topinka et al., 2013). Despite the multiple effects related to the presence of PAHs in PM, there is still not enough evidence on the harmful effects of these substances; this is due in part to the fact that PAHs have a wide variety of physical and chemical properties that make their measurement difficult and expensive. In addition to the above, PAHs are usually present in small concentrations, making it difficult to carry out experimental exposure tests with biological models.

Something similar occurs with BC, a constituent of $PM_{2.5}$ and UFP, which has been related to respiratory alterations (Paunescu et al., 2019) and cardiovascular functions (Gao and Sang, 2020). As a fine particle, BC can be inhaled and consequently deposited in the lungs, becoming more harmful to people than other contaminants such as

Table 2
Human toxicological studies related to UFPs exposure (<100 nm).

Age Group	Number of subjects	Study area	Country	UFPs quantification methodology	Biological test	Key findings	Reference
Adults	58	Indoor and outdoor environments	Copenhagen	Personal monitors for UFPs collection, CPC, Gravimetry for $PM_{2.5}$	Endothelial progenitor cell levels by polychromatic flow cytometry; ROS production in leukocytes by flow cytometry with 2,7-dichlorofluorescein in blood.	Positive correlation between the levels of endothelial progenitor cells and the concentration of UFPs from external environments. No correlation with leukocyte-mediated oxidative stress.	Jantzen et al. (2016)
Children	655	Schools	Australia	CPC, TSI Model 3781 and TSI Model 3787. For particles larger than 6 nm and 5 nm, respectively.	Pulmonary function of children was assessed by interviewing their parents, spirometry, measurement of exhaled nitric oxide and serum C-reactive protein	UFPs did not affect the children's respiratory health, but they show systemic effects, detected in the form of a positive association with a biomarker for systemic inflammation.	Clifford et al. (2018)
Adults	22	Public parks at the LAX International Airport	USA	DiscMini diffusion charger (Testo AG), CPC 3007, TSI Inc, and an Aethalometer E51 to measure BC	Participants carried out a soft walking activity scheduled twice in public parks inside and outside the influence area. Spirometries were performed, exhaled nitric oxide, and circulating inflammatory cytokines before and after exposure were measured.	Existence of acute systemic inflation after exposure to UFPs related to the airport was demonstrated. The effects related to road traffic exposure were different.	Habre et al. (2018)
Newborns	158–743	Urban	Canada	Concentration of UFPs with software	Prenatal exposure (between the second and eighth week after conception, when the heart begins to form, risk of congenital heart defects) to UFPs	UFPs exposure was associated with an increased risk of the ventricular septal defect.	Lavigne et al. (2019)
Adults	50	Urban	Italy	Portable UFP monitors	Correlation between exposure to ultrafine particle concentrations and heart rate in a healthy population.	Short-term exposure to concentrations of UFPs is positively associated with heart rate for the evaluated people's different physical activities.	Rizza et al. (2019)
Children	305	Urban	France	Concentrations to BC and UFP with Portable monitors.	Forced expiratory volume in 1 s (FEV1), forced vital capacity (FVC), and the fraction of exhaled nitric oxide (FeNO) was determined in children's exposure for 24 h.	Increase in 24-hour. BC exposure concentrations were related to a statistically significant decrease in lung function parameters only among children with persistent respiratory symptoms	Paunescu et al. (2019)

PM_{10}, $PM_{2.5}$ and inorganic particles (Kumar et al., 2018; Magalhaes et al., 2018; Zhang et al., 2019). BC particles are toxic through mechanisms of oxidative stress, cell signalling and activation, and the release of mediators initiating inflammatory processes in the respiratory tract (Nho, 2020) and the cardiovascular system (Paunescu et al., 2019). Besides, as a fine aerosol with a large specific surface area, BC can absorb carcinogenic contaminants, such as VOCs and PAHs, which can settle on the skin or even be inhaled, reaching the lungs; thus, affecting respiratory organ tissues. BC produces more harm to people than other contaminants, such as fine (2.5 μm) and coarse (10 μm) PM (Magalhaes et al., 2018; Zhang et al., 2019).

In addition to the toxicological effects mentioned previously, recent studies showed that UFPs have greater power to induce epigenetic modifications than larger particles (Wong et al., 2017; Bhargava et al., 2019). These modifications are mediated by an increase in the production of oxidizing species, which give rise to oxidative stress in the cells and activate inflammatory responses that then lead to epigenetic alterations of the miRNA. Hence, the epigenetic modifications (Wong et al., 2017). Likewise, UFPs lead to higher levels of DNA methyltransferase expression related to global changes in DNA methylation. Additionally, there may be changes in the histone code and mRNA transcription error, and protein translation levels in cells exposed to these particles (Bhargava et al., 2019). In addition to the above, Shukla et al. (2019) found that DNA modification may persist through downstream generations and result in the transgenerational epigenomic inheritance.

3.3. Human toxicity studies

Weak evidence of an association between daily UFPs and mortality has been found in epidemiological studies in several cities of Europe (Stafoggia et al., 2017). Similarly, in a regression study in cities in Germany and Eastern Europe, they observed positive but not statistically significant associations between prolonged exposures to UFPs and respiratory mortality (Lanzinger et al., 2016). However, in some time-series analyses and case-crossover studies performed in China, they identified sufficient information to support significant short-term mortality effects of various air pollutants, such as PM_{10}, $PM_{2.5}$, SO_2, NO_2, and O_3.

Evidence from studies in different parts of the world relates high concentrations of UFPs with acute and chronic effects on human health, including systemic effects, neuronal deficiencies (Cory-Slechta et al., 2018) and neurological diseases, as well as cataracts, diabetes, health deficiencies in newborns, and behavioural alterations (Fleischer et al., 2014; Agudelo-Castañeda et al., 2017; Shukla et al., 2019). Likewise, it has been found that particles with an aerodynamic diameter less than 2.5 μm can exacerbate inflammatory diseases such as asthma and acute bronchitis; they can also cause acute heart attacks and contribute to chronic diseases such as diabetes or cardiovascular disease or they may have a role in lung cancer (Marabini et al., 2017). Tables 2 and 3 summarize some of the toxicological studies carried out in recent years in humans and human cells, respectively.

Some studies have found that children represent the most vulnerable group regarding exposure to fine particles and UFPs due to their state of growth and ways of exposure compared to adults (Da et al., 2019; Slezakova et al., 2019). Likewise, they lack a fully developed defence mechanism for detoxification, they inhale a more significant amount of air volume per body weight, and have a different metabolism (Burtscher and Schüepp, 2012; Da et al., 2019). It has also been found that adults of advanced ages and pregnant women are included in the population vulnerable to atmospheric particles. For the latter case, a recent study found an association between the increase in the concentration of UFPs in the air with adverse effects on blood pressure and systemic inflammation in healthy adults (Liu et al., 2018). Participants in this study were interviewed and examined periodically between 2014 and 2017; particle concentration was also monitored during this time.

Table 3
Toxicological studies related to UFPs exposure (<100 nm) in human cells.

Type of cells	UFPs quantification methodology	Biological test	Key findings	Reference
A549	Three multi-stage impactors. Analysis of samples by gravimetric and identification of ions soluble in water, total carbon, PAHs and anhydrous sugar.	Genotoxicity in A549 cells (human lung carcinoma cells) exposed to UFPs from wood and firewood combustion was evaluated.	The presence of significant DNA damage was obtained after 24h of treatment.	Marabini et al. (2017)
THP-1; Human monocytes from 8 non-smoker female donors	UFPs monitoring (40 days) with a Hi-vol PTFE filter. Total organic carbon (TOC): Sievers analyzer. Metals: quantified by mass spectrometry de inductively coupled (SF-ICP-MS)	Exposure (24 h) to UFPs using aqueous suspensions. Cellular cytotoxicity: measured using lactate dehydrogenase (LDH) with an LDH colorimetric assay kit; ROS formation: measured through the 2′,7′-dichlorofluorescein diacetate and microplates to measure fluorescence. Cytokine levels were measured with an ELISA kit (human TNF-α)	Correlation between exposure to UFPs and oxidative inflammatory responses. Increased ROS formation in THP-1 cells	Bliss et al. (2018)
Embryonic stem cells hESC	Ultrafine carbon nano-powder (Sigma -Aldrich) was used. Characterization of the particles by FE-SEM coupled with X-rays (EDS)	Cell viability assays, immunofluorescence staining tests, RNA extraction and RT-PCR analysis, were performed; protein extraction and quantification utilizing the BCA protein kit.	Exposure to carbon particles altered the differentiation of keratinocytes and genes related to inflammation and psoriasis	Cheng et al. (2020)
A549 human lung cancer cells	Four-stage cascade impactor sampling on quartz filters in a city in China. Characterization by AFM (atomic force microscopy)	Tumour endothelium adhesion assays, protein extraction after cell exposure following separation by sodium dodecyl sulphate polyacrylamide gel electrophoresis (SDS-PAGE), Western blot assays, enzyme ligand immunosorbent assay (ELISA), Immunofluorescence and immunoprecipitation assay.	The UFPs stimulated the release of HMGB1, induced the production of pro-inflammatory cytokines facilitated by NFkB through the interaction of HMGB1 with RAGE and resulted in the adhesion of cancer endothelial cells.	Gao and Sang (2020)
Lung cells (BEAS-2B and NCI-H292) and human bronchial epithelial cells (NHBE)	The particles were collected in northern France with a High Volume Impactor. Trace metals: measured by ICP-MS, PAHs by high precision liquid chromatography.	Comet, micronucleus and erythrocyte-based Pig-A gene mutation assays in vivo by flow cytometry	Fine particles and UFPs lack a genotoxic effect in vitro on primary NHBE cells. In contrast, positive results were obtained in the comet assay on BEAS-2B and NCI-H292 immortalized cell lines.	Platel et al. (2020)

Effects related to PM environmental exposure also include significant developmental neurotoxicity, a principal reason for developing diseases such as autism, Alzheimer's, and Parkinson's, where age adversely impacts neurotoxic damage, mainly due to PM's ability to generate ROS, induce oxidative stress, inflammatory response, mitochondrial deterioration, DNA damage, and other mutagenic activities (Shukla et al., 2019).

Recently, epidemiological studies have investigated the association of environmental exposure to UFPs with cardiopulmonary morbidity and mortality (Lanzinger et al., 2016; Liu et al., 2018). There is an association between increased UFPs levels and adverse effects on high blood pressure and systemic inflammation (Liu et al., 2018). Due to the size, UFPs have high alveolar deposition, a large surface area with adhered toxins, and can penetrate blood vessels, which may initiate oxidative stress and inflammation with subsequent atherosclerotic progression leading to thrombus formation (Møller et al., 2020).

Another determining factor in UFP's toxicity is the emission source, on which the concentration of pollutants on the surface of the particles depends. For instance, in a study conducted on people living less than 75 m away from a main road or highway, it was found that exposure to road traffic increases the risk of stroke with strong associations with ischemic stroke. Likewise, hourly or daily changes regarding pollutant concentrations were also related to an increased risk of stroke and stroke mortality, being this last risk linked to UFPs (Sade et al., 2015).

Concerning the above, Bourdrel et al. (2017) found that air pollution, particularly diesel exhaust, provokes a dramatic increase in ROS generation, which alters nitric oxide-mediated vasodilation and promotes vascular inflammation. These acute functional consequences of air pollution exposure have been demonstrated in regulating myocardial and pulmonary blood flow, and coagulation function. Combustion-derived particles have substantial adverse effects attributed to the small size of these UFPs and the PAHs and metals carried on their surface. Although UFPs have a substantial cardiovascular effect, their atmospheric concentrations are strongly underestimated according to standards (Bourdrel et al., 2017).

At the cellular level, effects such as inflammation (Habre et al., 2018; Xia et al., 2018), DNA damage, and genomic instability have been evidenced (Marabini et al., 2017). When having genomic instability, there is a high probability that the cell develops and accumulates genome alterations, which can lead to carcinogenic processes. These alterations' frequency is related to the loss of fidelity in mechanisms such as DNA replication, chromosomal segregation, DNA repair, and cell cycle progression (Santibáñez-Andrade et al., 2017).

An *in vitro* study with human embryonic stem cells revealed that ultrafine carbon particles could cause skin inflammation and psoriasis. Children are the most susceptible to such pollutants, mainly when they have not been born and are still in the womb. Premature skin ageing, accompanied by high risks for skin inflammation diseases, such as atopic dermatitis and psoriasis, has been proved to increase in children exposed to air pollution (Cheng et al., 2020).

3.4. Biological models and toxicity studies

Laboratory bioassays that use organisms *in vivo* are essential tools to clarify the PM constituents' toxic action mode, identifying markers that discriminate the different potential toxins of atmospheric PM samples (Zhang et al., 2011). Several organisms have been used in *in vivo* studies regarding atmospheric particle toxicity, including rats (Sydbom et al., 2001; Zhang et al., 2011), mice (Morris-Schaffer et al., 2018), cats (Sydbom et al., 2001), birds (Cui et al., 2018), wild rodents (Gómez-Ugalde, 2003), snails (De Roma et al., 2017), fish (Gonzalez-Moragas et al., 2015), and nematodes (Zhao et al., 2014; Gonzalez-Moragas et al., 2015; Chung et al., 2019; Marimon-Bolívar et al., 2019; Sinis et al., 2019; Wu et al., 2019). For example, Zhang et al. (2011) used rats and found that the smaller the particle size, the greater the lungs' inflammatory effects, and consequently, the DNA damage. Other

Table 4
Toxicological studies related to exposure to UFPs (<100nm) in biological models.

Study	UFPs quantification methodology	Biological test	Key findings	References
Mouse pups	CPC and SMPS for characterization of UFPs	Postnatal exposure (4–7 and 10–13) equivalent to the human third trimester at UFP concentrations similar to those of vehicular traffic in full-length exposure chambers.	Neurotoxicity, related to autism. Inflation and oxidative stress are associated as mechanisms	Allen et al. (2017)
Mouse pups	HUCAPS inhalation exposure chambers from a high volume UFP concentrator were used to concentrate environmental particles generated on a nearby busy road.	The offspring were exposed for 4 h to concentrated UFPs (10–20 times) using a HUCAPS kit. Exposure was done on postnatal days 4–7 and 10–13. Behavioural tests were carried out.	Learning and memory deficits; memory, impulsive behaviours, behavioural problems.	Cory-Slechta et al. (2018)
Mice	Aethalometer	Maternal exposure to BC particles during pregnancy in female mice	Neurotoxic effects on fetuses. Persistent pathological changes in the tissues of the cerebral cortex and impaired cerebrovascular function in offspring.	Zhang et al. (2019)
Mice	Intranasal exposure of BALB/c mice to FP and UFPs. The particles were collected in northern France with a High Volume Impactor (HVIS, 400 L/min flow). Trace metals were measured by ICP-MS, PAHs, by high precision liquid chromatography.	Genotoxic effects were evaluated using (i) liver and lung in vivo comet assay, (ii) bone marrow in vivo micronucleus test, and (iii) in vivo test. Mutation test of the Pig-A gene in peripheral blood, at doses of 10 and 100 μg per animal.	FP and UFP do not show genotoxic/mutagenic activity in vivo under the conditions analyzed.	Platel et al. (2020)
Mice	BC was measured using Transmission Electron Microscopy (TEM) instrument and a field emission Scanning Electron Microscopy (SEM). SMPS dynamically monitored the diameter of BC particles	Thirty-six male mice (C57BL/6) were exposed to BC particles in inhalation chambers for 6 h per day for 28 continuous days. The activities of antioxidant enzymes (CAT, SOD, GSH-Px) and ROS were evaluated in the lungs and cells. Apoptosis-related proteins were tested by Western blotting, immunohistochemistry, and real-time PCR	The reduction of antioxidant enzyme activities and the addition of ROS in BC exposure groups were observed, and the gene and apoptosis-related protein levels were increased in BC exposure mice. The BC-treated cells were consistent with those of mice, and the apoptosis rate was increased in BC treated cells.	Li et al. (2020)

toxicological studies that were carried out in recent years on biological models are listed below (Table 4).

Wardoyo et al. (2018) conducted a study with mice where they found that the exposure to UFPs from motorcycle emissions have a significant effect since these particles can penetrate the pulmonary alveoli and subsequently deposit themselves in the kidney leading to renal cells deformation. The exposure to these type of particles results in alterations in glomerular and tubular epithelial cells; along these lines, the concentration of UFPs determines the deformation of such cells.

Besides, Wardoyo et al. (2018) found a positive correlation between total concentrations of UFPs in motorcycle exhaust emissions and physical damage in mice kidneys; this damage goes back to oxidative stress. Inhaled UFPs can deposit themselves in the lungs, coagulate, agglomerate, penetrate the pulmonary alveoli, enter the bloodstream, and subsequently reach vital organs, causing disorders like the case mentioned above. Similar results were previously reported by Sydbom et al. (2001). Other studies carried out with mice have found that UFPs can lead to neurological effects (Morris-Schaffer et al., 2018), such as memory loss (Cory-Slechta et al., 2018), behavioural problems, and changes in brain tissues (Zhang et al., 2019).

4. Capturing, measuring and controlling UFPs

4.1. Capture and measurement mechanisms

As mentioned earlier, the UFPs concentration in air is measured and expressed commonly in particle number (PN) per unit volume (Kwon et al., 2020). In most published studies where the particle number and size distribution are reported, researchers use condensation particle counters (CPCs) and electrostatic classifiers (ECs). Moreover, the measurement of particles up to 0.4 nm is made using ion mobility air spectrometers (Morawska et al., 2008; Kumar et al., 2014). Fig. 4 presents the general diagram of the operation of the typical methodologies used to measure UFPs.

In the CPC methodology, particles are initially enlarged by the vapour's condensation until a size is detectable, and then they are counted while passing through a laser beam (Da et al., 2019). Thus, the detection of the particles is done by optical methods. According to the instrument characteristics, this process will allow counting particles up to 3 nm in diameter (HEI, 2013). These instruments can be used in different combinations with other particle meters, such as differential mobility analyzers (DMAs), to separate the particles by size before condensation. Among the limitations presented by the CPCs are their high cost and their limited range regarding particle size.

One of the recently developed equipment is the portable optical particle counter (OPC) based on light scattering. However, these devices cannot accurately measure particles smaller than 300 nm, and thus, they are not considered adequate to determine UFPs (Kim et al., 2018). In a review published by Kumar et al. (2010), the equipment mentioned above's main commercial models were listed, and a classification of them is presented by particle size range.

There are also methods based on ECs that classify the particles according to size. In this methodology, electrically charged particles move and are separated by size when they are in contact with a high voltage electric field (Forti et al., 2005). These instruments work in combination with particle counters such as differential mobility/scanning particle classifiers, e.g. Differential mobility particle sizer (DMPS) or scanning mobility particle sizer (SMPS), and differential mobility spectrometers (DMS). The SMPS is a high-resolution nanoparticle meter that uses electrostatic classificationthe (Agudelo-Castañeda et al., 2019).

Other types of equipment used are UFP monitors, laser aerosol spectrometer (LAS) with optical detection, and instruments manufactured by GRIMM Aerosol Technik Ainring GmbH & Co. KG that include combinations of SMPS, DMA, and CPC systems to measure particles (5–1110 nm) (Kumar et al., 2010). Low-pressure electric impactors (ELPI), aerodynamic particle sizer (APS) have also been used, but unfortunately, this

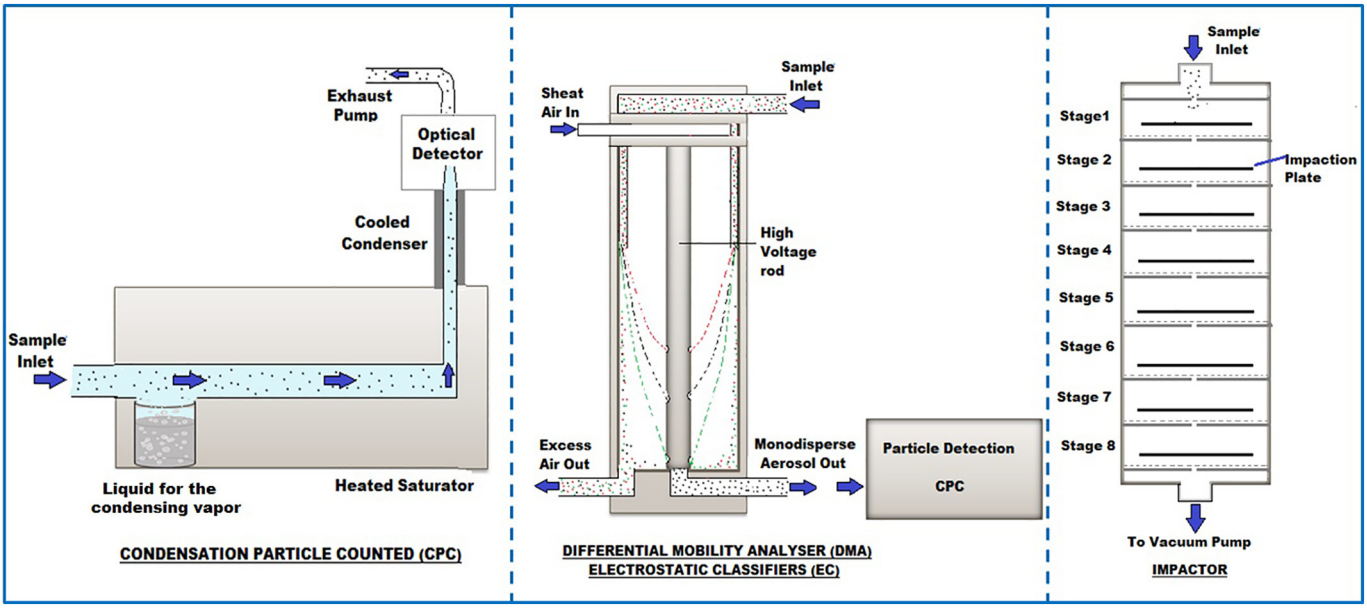

Fig. 4. Principles of operation of the main methodologies used to capture and measure UFPs.

equipment is mainly used for research purposes and, because of their high price, is not included in monitoring systems of air quality.

Unlike fine or coarse particles, which are unanimously agreed to be measured by mass-sensitive methods, there is still little consensus on whether UFPs should be better characterized by mass, volume, surface area/numerical concentrations or chemical properties. One of the latest methodologies developed to determine the size distribution of the number of UFPs is based on electrically charged particles, separated in an electric field, according to the particles' electric mobility. This family of instruments is called mobility particle size spectrometers (Kim et al., 2018). Within this family of instruments, we can mention the Testo DiSCmini, which is a miniature and portable handheld diffusion size classifier that obtains the concentration of the particles by measuring the electric current produced by the deposition of the charged particles in its two different stages (Luengo-Oroz and Reis, 2019).

$PM_{0.1}$ concentrations are typically less than 1 μg/m^3, and commercial scales generally have detection limits of ± 1–5 μg for means of collection (e.g. filters). Mainly, for UFPs' collection, researchers use the cascading impactors, in which the particles can be separated into different fractions. Aerosol mass spectrometers and aerosol mass flight time spectrometers have also been developed; these last two can measure the chemical composition of UFPs for short periods. In these methods, the sampled particles are initially broken down into ions, following their main components, and then analyzed by mass spectrometry (HEI, 2013).

When sampling UFPs in a filter, different methods for their physicochemical characterization can be used. Among the most common methods are transmission electron microscopy (TEM) along with energy-dispersive X-ray spectroscopy (TEM-EDS), scanning electron microscopy along with energy-dispersive X-ray spectroscopy (SEM-EDS), and X-ray fluorescence (XRF) spectrometry with synchrotron radiation. These methods are used to obtain morphological and chemical information about the particles. Nano aerosol mass spectrometry (NAMS) with TEM-EDS is used for size identification and elemental analysis; there are three nanoparticle sampling forms: (i) aerodynamic sampling, (ii) electrostatic sampling, and (iii) thermophoretic sampling. The aerodynamic sampling method involves the use of the impactors mentioned above. In the electrostatic sampling, particles with a unipolar or bipolar charge are deposited directly in the TEM network by electrostatic forces via ultrafine aerosol time-of-flight mass spectrometry (UF-ATOFMS) (Bzdek et al., 2012).

In the case of BC, and since this pollutant has great variability due to both meteorological factors and pathways or distance from the generating sources, researchers use mobile monitoring with portable and fixed micro-aethalometers with aethalometers simultaneously with GPS to indicate the location (Van den Bossche et al., 2015; Tran et al., 2020). A challenge for monitoring UFPs, besides the detection limit, is measuring personal exposure to these particles due to the weak spatial correlation (Weichenthal et al., 2016), probably due to background concentrations in the fixed monitoring stations. Table 5 presents a summary of the main analytical methods used for sampling and the characterization of UFPs since 2008.

4.2. Control mechanisms

Among the management mechanisms taken to ensure that the concentration of atmospheric particles does not exceed the authorized levels, affect human health, cause damage to flora, fauna or the environment in general, direct and indirect measures are developed. Indirect measures include all those actions aimed at preventing particle concentration from exceeding primary value limits; for instance, urban planning and territorial sanitation, air quality plans, information and awareness campaigns, sustainable mobility programs, control measures in different sectors, vehicle technology renewal, and fuel quality improvement (Morawska et al., 2008; Azarmi et al., 2014).

Direct measures are actions designed to reduce the particles' concentration through different control equipment; these are particle traps, which effectively control the solid fraction of the emitted exhaust particles, including elemental carbon (soot) and black smoke. Filters, wet particle scrubbers, electrostatic precipitators, and inertial impactors are also included. In electrostatic precipitators, particles of sizes between 0.1 μm and 1.0 μm are captured and operated at high gas temperatures (up to 1200 °F) (Morawska et al., 2008; Miller, 2011; Vallero, 2011; Pyo et al., 2017).

An alternative filtration method without filters is the use of water vapour condensation for UFPs. This method enables the growth of any type of UFPs in the form of a water droplet. Once UFPs have grown in diameter, these particles are easy to remove (Pyo et al., 2017).

Table 5
Methodologies for the measurement and analysis of contaminants present in UFPs.

Country	Emission source type	Characterization and measurement methods	Contaminants identified	Mean UFPs concentration[a]	Reference
China	Urban zone	Sampling: 13-stage MOUDI Impactor. Characterization: SEM-EDX, SRXRF	Fine and ultrafine particles. Elements: Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Br, Rb, Sr and Pb	Coarse, fine and ultrafine particles: 9.38 ± 2.18, 8.82 ± 3.52 and 2.02 ± 0.41 μg/m^3, respectively.	Lü et al. (2012)
United Kingdom	Particles from concrete mixing	Mass distribution of particles: GRIMM particle spectrometer and DMS	Particle diameter: 5–10,000 nm	(21.27 ± 2.02) ×10^3 to (732.27±442.51) ×10^3 PN/cm^3	Azarmi et al. (2014)
Brazil	Urban area with high vehicular traffic	Measure concentration: NanoScan SMPS TSI	Particle diameter: 10–420 nm	4.85×10^4 PN/cm^3 to 1.80×10^3 PN/cm^3	Schneider et al. (2015)
Italy	Urban transport	Measure concentration: CPC – TSI P-Trak	Particle diameter: 20–1000 nm.	Car: 5249–48,428 PN/cm^3; Motorcycle 73,168 PN/cm^3, bus 29,299 PN/cm^3	Grana et al. (2017)
China	Urban zone	Sampling: MOUDI Impactor	Particle diameter: 0.05–0.1 μm	UFPs (μg/m^3): 1.47 ± 0.88; range between 0.14 and 3.31.	Liu et al. (2018)
Greenland	Urban zone	Sampling: CPC – TSI P-Trak	Particle diameter: < 0.1 μm ($PM_{0.1}$) in waste incineration plant (1), an area with high Vehicular traffic (2), a site close to buildings (3) and an airport (4).	(1) 478–125,005 PN/cm^3; (2) 450–77,009 PN/cm^3; (3) 5470–43,422 PN/cm^3 and (4) 44,741 PN/cm^3	Pétursdóttir et al. (2018)
Belgium	Vehicular traffic	MicroAeth ethalometer for BC and a fixed aethalomete. UFPs concentrations: CPC – TSI P-Trak. Metals characterization: HR-ICP-MS	BC, UFPs and elements: Na, K, Rb, Mg, Ca, Sr, Ti, V, Cr, Mo, Mn, Fe, Co, Rh, Ni, Pd, Pt, Cu, Ag, Zn, Cd, Al, Pb, As, Sb, Se, U.	3.3 μg/m^3 to 13,391 PN/cm^3 for BC and UFPs, respectively.	Hofman et al. (2018)
Brazil	Urban area	Measure concentration: NanoScan SMPS TSI	Particle diameter: 2.5–250 nm, UFPs, PM_{10}, NO, NO_2, O_3 and SO_2	Particle levels in mornings: 20,245–21,945 PN/cm^3; nights: 21,281–21,071 PN/cm^3	Agudelo-Castañeda et al. (2019)
Mexico	Urban zone	Aethalometer for monitoring BC in real-time.	BC	0.27–0.75 μg/m^3	Peralta et al. (2019)
Italy	Different workplaces	Three-stage DLPI (Dekati Low-Pressure Impactor) with polyurethane filters. Gravimetric analysis: Sartorius MC5 microbalance	Particle diameter: < 0.1 μm ($PM_{0.1}$)	4.7–19.8 μg/m^3	Buiarelli et al. (2019)
Portugal	Air traffic	CPC - TSI P-Trak	UFPs	2.3×10^5 to 3.4×10^5 PN/cm^3	Lopes et al. (2019)
Global	Urban area	CPC TSI; DMPS / CPC; SMPS / CPC TSI; DMPS	UFPs y $PM_{2.5}$	Annual averages: 8.0×10^3 to 19.5×10^3 PN/cm^3 for UFPs and 7.0–65.8 μg/m^3 for $PM_{2.5}$	de Jesus et al. (2019)
United Kingdom	Urban area	Testo DiSCmini nanoparticle counter	UFPs in PN/cm^3	7990 and 19,310 PN/cm^3	Luengo-Oroz and Reis (2019)
Ghana	Elementary schools	Three Aerasense Nano Tracers	Particles: 10–300 nm; 20–120 nm	1.83×10^4 to 8.93×10^4 PN/cm^3	Nyarku et al. (2019)
United States	Urban area	UFPs concentration: CPC. SPMS, NAMS and BC monitor to measure particle size	Measurement of UFPs, $PM_{2.5}$, CO and NO_2	7500 ± 1000 PN/cm^3 at bottom sites. For local roads 11,000 ± 1200 PN/cm^3. Close to restaurants 15,800 ± 1300 PN/cm^3; High traffic roads: 15,000 ± 2400 PN/cm^3	Saha et al. (2019)
United Kingdom	Air traffic	Particle number: CPC TSI. Particle classifiers: TSI with long DMA classifier and TSI DMA, both with SMPS technology	UFPs. Other pollutants: PM_{10}, $PM_{2.5}$, NO_x and BC	UFPs: 2637–10,046 PN/cm^3	Stacey et al. (2020)
Germany	Urban area	MPSS, CPC TSI and TSI electrometer	Particle size distribution and BC. Particles from 20 nm to 800 nm	Particles: 900 PN/cm^3, BC: 0.1–2.3 μg/m^3	Sun et al. (2019)

[a] PN: particle number

5. Conclusions

According to the findings reported in the literature, the importance of continuing to carry out studies about UFPs is highlighted because they have been related to various conditions in people's health that contribute to the rise in morbidity and mortality rates worldwide. Among the main toxicological mechanisms associated with UFPs is the oxidative stress generated from reactive oxygen species associated with contaminants such as metals, PAHs, and BC. In this sense, the main effects found include respiratory problems such as asthma and chronic obstructive pulmonary disease, pulmonary fibrosis, neurodegenerative diseases, cardiovascular diseases, DNA changes generated from epigenetic changes, and genotoxic, mutagenic and carcinogenic activity.

Finally, despite the findings reported in this article and that there are multiple mechanisms for the measurement and control of atmospheric UFPs, it is necessary to continue in the study of the different effects of particulate material in order to obtain sufficient evidence that leads to the establishment of new public policies and measures for effective pollution prevention and control.

Declaration of Competing Interest

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

Acknowledgments

This work was carried out by partial financial support from Colciencias, Colombia (Project 141180764164, Contract 815-2018). Special thanks to Prof. Camilo A. Castro for his suggestions towards the literature review approach.

References

Abbas, I., Badran, G., Verdin, A., Ledoux, F., Roumié, M., Courcot, D., Garçon, G., 2018. Polycyclic aromatic hydrocarbon derivatives in airborne particulate matter: sources, analysis and toxicity. Environ. Chem. Lett. 16, 439–475. https://doi.org/10.1007/s10311-017-0697-0.

Abdel-Shafy, H.I., Mansour, M.S.M., 2016. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egypt. J. Pet. 25 (1), 107–123. https://doi.org/10.1016/j.ejpe.2015.03.011.

Abramesko, V., Tartakovsky, L., 2017. Ultrafine particle air pollution inside diesel-propelled passenger trains. Environ. Pollut. 226, 288–296. https://doi.org/10.1016/j.envpol.2017.03.072.

Agudelo-Castañeda, D.M., Teixeira, E.C., Schneider, I., Lara, S.R., Silva, L.F.O., 2017. Exposure to polycyclic aromatic hydrocarbons in atmospheric $PM_{1.0}$ of urban environments: Carcinogenic and mutagenic respiratory health risk by age groups. Environ. Pollut. 224, 158–170. https://doi.org/10.1016/j.envpol.2017.01.075.

Agudelo-Castañeda, D.M., Teixeira, E.C., Braga, M., Rolim, S.B.A., Silva, L.F.O., Beddows, D.C.S., Harrison, R.M., Querol, X., 2019. Cluster analysis of urban ultrafine particles size distributions. Atmos. Pollut. Res. 10 (1), 45–52. https://doi.org/10.1016/j.apr.2018.06.006.

Allen, J.L., Oberdörster, G., Morris-Schaffer, K., Wong, C., Klocke, C., Sobolewski, M., Conrad, K., Mayer-Proschel, M., Cory-Slechta, D.A., 2017. Developmental neurotoxicity of inhaled ambient ultrafine particle air pollution: Parallels with neuropathological and behavioral features of autism and other neurodevelopmental disorders. Neurotoxicology 59, 140–154. https://doi.org/10.1016/j.neuro.2015.12.014.

Azarmi, F., Kumar, P., 2016. Ambient exposure to coarse and fine particle emissions from building demolition. Atmos. Environ. 137, 62–79. https://doi.org/10.1016/j.atmosenv.2016.04.029.

Azarmi, F., Kumar, P., Mulheron, M., 2014. The exposure to coarse, fine and ultrafine particle emissions from concrete mixing, drilling and cutting activities. J. Hazard. Mater. 279, 268–279. https://doi.org/10.1016/j.jhazmat.2014.07.003.

Azarmi, F., Kumar, P., Marsh, D., Fuller, G., 2016. Assessment of the long-term impacts of PM_{10} and $PM_{2.5}$ particles from construction works on surrounding areas. Environ. Sci.: Process. Impacts 18 (2), 208–221. https://doi.org/10.1039/c5em00549c.

Badran, G., Ledoux, F., Verdin, A., Abbas, I., Roumie, M., Genevray, P., Landkocz, Y., Guidice, J.M.L., Garçon, G., Courcot, D., 2020. Toxicity of fine and quasi-ultrafine particles: Focus on the effects of organic extractable and non-extractable matter fractions. Chemosphere 243, 125440. https://doi.org/10.1016/j.chemosphere.2019.125440.

Bhargava, A., Tamrakar, S., Aglawe, A., Lad, H., Kumar, R.S., Kumar, D., Tiwari, R., Chaudhury, K., Yu, I., Kumar, P., 2018. Ultrafine particulate matter impairs mitochondrial redox homeostasis and activates phosphatidylinositol 3-kinase mediated DNA damage. Environ. Pollut. 234, 406–419. https://doi.org/10.1016/j.envpol.2017.11.093.

Bhargava, A., Shukla, A., Bunkar, N., Shandilya, R., Lodhi, L., Kumari, R., Gupta, P.K., Rahman, A., Chaudhury, K., Tiwari, R., Goryacheva, I.Y., Mishra, P.K., 2019. Exposure to ultrafine particulate matter induces NF-κβ mediated epigenetic modifications. Environ. Pollut. 252, 39–50. https://doi.org/10.1016/j.envpol.2019.05.065.

Billet, S., Landkocz, Y., Martin, P.J., Verdin, A., Ledoux, F., Lepers, C., André, V., Cazier, F., Sichel, F., Shirali, P., Gosset, P., Courcot, D., 2018. Chemical characterization of fine and ultrafine PM, direct and indirect genotoxicity of PM and their organic extracts on pulmonary cells. J. Environ. Sci. 71, 168–178. https://doi.org/10.1016/j.jes.2018.04.022.

Bliss, B., Tran, K.I., Sioutas, C., Campbell, A., 2018. Ambient ultrafine particles activate human monocytes: Effect of dose, differentiation state and age of donors. Environ. Res. 161, 314–320. https://doi.org/10.1016/j.envres.2017.11.019.

Bourdrel, T., Bind, M.A., Béjot, Y., Morel, O., Argacha, J.F., 2017. Cardiovascular effects of air pollution. Arch. Cardiovasc. Dis. 110 (11), 634–642. https://doi.org/10.1016/j.acvd.2017.05.003.

Briffa, J., Sinagra, E., Blundell, R., 2020. Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon 6 (9), e04691. https://doi.org/10.1016/j.heliyon.2020.e04691.

Buiarelli, F., Di Filippo, P., Massimi, L., Pomata, D., Riccardi, C., Simonetti, G., Sonego, E., 2019. Ultrafine, fine and coarse airborne particle mass concentration in workplaces. Atmos. Pollut. Res. 10 (5), 1685–1690. https://doi.org/10.1016/j.apr.2019.06.009.

Buonanno, G., Stabile, L., Avino, P., Belluso, E., 2011. Chemical, dimensional and morphological ultrafine particle characterization from a waste-to-energy plant. Waste Manage. 31 (11), 2253–2262. https://doi.org/10.1016/j.wasman.2011.06.017.

Burtscher, H., Schüepp, K., 2012. The occurrence of ultrafine particles in the specific environment of children. Paediatr. Respir. Rev. 13 (2), 89–94. https://doi.org/10.1016/j.prrv.2011.07.004.

Buzea, C., Pacheco, I., 2019. 28 - Toxicity of nanoparticles. In: Pacheco-Torgal, F., Diamanti, M.V., Nazari, A., Granqvist, C.G., Pruna, A., Amirkhanian, S. (Eds.), Nanotechnology in Eco-efficient Construction. Woodhead Publishing Series in Civil and Structural Engineering, Cambridge, pp. 705–754 https://doi.org/10.1016/b978-0-08-102641-0.00028-1.

Buzea, C., Pacheco, I.I., Robbie, K., 2007. Nanomaterials and nanoparticles: Sources and toxicity. Biointerphases 2, MR17–MR71. https://doi.org/10.1116/1.2815690.

Bzdek, B.R., Pennington, M.R., Johnston, M.V., 2012. Single particle chemical analysis of ambient ultrafine aerosol: A review. J. Aerosol Sci. 52, 109–120. https://doi.org/10.1016/j.jaerosci.2012.05.001.

Castro-Rodriguez, J.A., Forno, E., Rodriguez-Martinez, C.E., Celedón, J.C., 2016. Risk and Protective Factors for Childhood Asthma: What Is the Evidence? J. Allergy Clin. Immunol. In Practice 4 (6), 1111–1122. https://doi.org/10.1016/j.jaip.2016.05.003.

Cervellati, F., Benedusi, M., Manarini, F., Woodby, B., Russo, M., Valacchi, G., Pietrogrande, M.C., 2020. Proinflammatory properties and oxidative effects of atmospheric particle components in human keratinocytes. Chemosphere 240, 124746. https://doi.org/10.1016/j.chemosphere.2019.124746.

Chen, R., Hu, B., Liu, Y., Xu, J., Yang, G., Xu, D., Chen, C., 2016. Beyond $PM_{2.5}$: The role of ultrafine particles on adverse health effects of air pollution. Biochim. Biophys. Acta (BBA), General Subjects 1860 (12), 2844–2855. https://doi.org/10.1016/j.bbagen.2016.03.019.

Chen, C., Zhao, Y., Zhang, Y., Zhao, B., 2017. Source strength of ultrafine and fine particle due to Chinese cooking. Procedia Eng. 205, 2231–2237. https://doi.org/10.1016/j.proeng.2017.10.062.

Chen, Q.Y., DesMarais, T., Costa, M., 2019. Metals and mechanisms of carcinogénesis. Annu. Rev. Pharmacol. Toxicol. 59, 537–554. https://10.1146/annurev-pharmtox-010818-021031.

Chen, X.C., Cao, J.J., Ward, T.J., Tian, L.W., Ning, Z., Kumar, N.G., Aquilina, N.J., Lam, S.H.Y., Qu, L., Ho, K.F., 2020. Characteristics and toxicological effects of commuter exposure to black carbon and metal components of fine particles (PM2.5) in Hong Kong. Sci. Total Environ 742, 140501. https://doi.org/10.1016/j.scitotenv.2020.140501.

Cheng, Z., Liang, X., Liang, S., Yin, N., Faiola, F., 2020. A human embryonic stem cell-based in vitro model revealed that ultrafine carbon particles may cause skin inflammation and psoriasis. J. Environ. Sci 87, 194–204. https://doi.org/10.1016/j.jes.2019.06.016.

Chu, B., Matti Kerminen, V., Bianchi, F., Yan, C., Petäjä, T., Kulmala, M., 2019. Atmospheric new particle formation in China. Atmos. Chem. Phys. 19 (1), 115–138. https://doi.org/10.5194/acp-19-115-2019.

Chung, M.C., Tsai, M.H., Que, D.E., Bongo, S.J., Hsu, W.L., Tayo, L.L., Lin, Y.H., Lin, S.L., Gou, Y.Y., Hsu, Y.C., Hou, W.C., Huang, K.L., Chao, H.R., 2019. Fine particulate matter-induced toxic effects in an animal model of caenorhabditis elegans. Aerosol Air Qual. Res. 19 (5), 1068–1078. https://doi.org/10.4209/aaqr.2019.03.0127.

Civeira, M., Pinheiro, R., Gredilla, A., De Vallejuelo, S., Oliveira, M., Ramos, C., Taffarel, S., Kautzmann, R., Madariaga, J., Silva, L.F., 2016. The properties of the nano-minerals and hazardous elements: potential environmental impacts of brazilian coal waste fire. Sci. Total Environ. 544, 892–900. https://doi.org/10.1016/j.scitotenv.2015.12.026.

Clifford, S., Mazaheri, M., Salimi, F., Ezz, W.N., Yeganeh, B., Low-Choy, S., Walker, K., Mengersen, K., Marks, G., Morawska, L., 2018. Effects of exposure to ambient ultrafine particles on respiratory health and systemic inflammation in children. Environ. Int. 114, 167–180. https://doi.org/10.1016/j.envint.2018.02.019.

Cory-Slechta, D.A., Allen, J.L., Conrad, K., Marvin, E., Sobolewski, M., 2018. Developmental exposure to low level ambient ultrafine particle air pollution and cognitive dysfunction. NeuroToxicology 69, 217–231. https://doi.org/10.1016/j.neuro.2017.12.003.

Crobeddu, B., Aragao-Santiago, L., Bui, L.C., Boland, S., Baeza, A.S., 2017. Oxidative potential of particulate matter 2.5 as predictive indicator of cellular. Environ. Pollut. 230, 125–133. https://doi.org/10.1016/j.envpol.2017.06.051.

Cui, J., Halbrook, R.S., Zang, S., Han, S., Li, X., 2018. Metal concentrations in homing pigeon lung tissue as a biomonitor of atmospheric pollution. Ecotoxicology 27 (2), 169–174. https://doi.org/10.1007/s10646-017-1882-4.

Cutruneo, C.M.N.L., Oliveira, M.L.S., Ward, C.R., Hower, J.C., de Brum, I.A.S., Sampaio, C.H., Kautzmann, R.M., Taffarel, S.R., Teixeira, E.C., Silva, L.F.O., 2014. A mineralogical and geochemical study of three Brazilian coal cleaning rejects: Demonstration of electron beam applications. Int. J. Coal Geol. 130, 33–52. https://doi.org/10.1016/j.coal.2014.05.009.

Da, Costa Oliveira, J.R., Base, L.H., de Abreu, L.C., Filho, C.F., Ferreira, C., Morawska, L., 2019. Ultrafine particles and children's health: Literature review. Paediatr. Respir. Rev. 32, 73–81. https://doi.org/10.1016/j.prrv.2019.06.003.

Dall'Osto, M., Thorpe, A., Beddows, D.C.S., Harrison, R.M., Barlow, J.F., Dunbar, T., Williams, P.I., Coe, H., 2011. Remarkable dynamics of nanoparticles in the urban atmosphere. Atmos. Chem. Phys. 11 (13), 6623–6637. https://doi.org/10.5194/acp-11-6623-2011.

Dalmora, A.C., Ramos, C.G., Querol, X., Kautzmann, R.M., Oliveira, M.L.S., Taffarel, S.R., Moreno, T., Silva, L.F.O., 2016. Nanoparticulate mineral matter from basalt dust wastes. Chemosphere (Oxford) 144, 2013–2017. https://doi.org/10.1016/j.chemosphere.2015.10.047.

De Kok, T.M.C.M., Driece, H.A.L., Hogervorst, J.G.F., Briedé, J.J., 2006. Toxicological assessment of ambient and traffic-related particulate matter: a review of recent studies. Mutat. Res. Rev. Mutat. Res. 613 (2-3), 103–122. https://doi.org/10.1016/j.mrrev.2006.07.001.

AQEG, 2017. Ultrafine Particles (UFP) in the UK. Air Quality Expert Group (AQEG). Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland. https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1807261113_180703_UFP_Report_FINAL_for_publication.pdf (accessed 30 December 2020).

De Oliveira Galvão, M.F., de Oliveira Alves, N., Ferreira, P.A., Caumo, S., de Castro Vasconcellos, P., Artaxo, P., de Souza Hacon, S., Roubicek, D.A., Batistuzzo de Medeiros, S.R., 2018. Biomass burning particles in the Brazilian Amazon region: Mutagenic effects of nitro and oxy-PAHs and assessment of health risks. Environ. Pollut. 233, 960970. doi:https://doi.org/10.1016/j.envpol.2017.09.068

De Roma, A., Neola, B., Serpe, F.P., Sansone, D., Picazio, G., Cerino, P., Esposito, M., 2017. Land Snails (Helix aspersa) as Bioindicators of Trace Element Contamination in Campania (Italy). O. A. Lib. Journal 4 (2), e3339. https://doi.org/10.4236/oalib.1103339.

De Vallejuelo, S.F.O., Gredilla, A., da Boit, K., Teixeira, E.C., Sampaio, C.H., Madariaga, J.M., Silva, L.F., 2017. Nanominerals and potentially hazardous elements from coal cleaning rejects of abandoned mines: Environmental impact and risk assessment. Chemosphere 169, 725–733. https://doi.org/10.1016/j.chemosphere.2016.09.125.

Dias, C.L., Oliveira, M.L.S., Hower, J.C., Taffarel, S.R., Kautzmann, R.M., Silva, L.F.O., 2014. Nanominerals and ultrafine particles from coal fires from Santa Catarina, South Brazil. Int. J. Coal Geol. 122, 50–60. https://doi.org/10.1016/j.coal.2013.12.011.

Donaldson, K., Stone, V., Clouter, A., Renwick, L., Macnee, W., 2001. Ultrafine particles. Occup. Environ. Med. 58, 211–216. https://doi.org/10.1136/oem.58.3.211.

Ehn, M., Thornton, J.A., Kleist, E., Sipilä, M., Junninen, H., Pullinen, I., Springer, M., Rubach, F., Tillmann, R., Lee, B., Lopez-Hilfiker, F., Andres, S., Acir, I.H., Rissanen, M., Jokinen, T., Schobesberger, S., Kangasluoma, J., Kontkanen, J., Nieminen, T., Kurtén, T., Nielsen, L.B., Jørgensen, S., Kjaergaard, H.G., Canagaratna, M., Maso, M.D., Berndt, T., Petäjä, T., Wahner, A., Kerminen, V.M., Kulmala, M., Worsnop, D.R., Wildt, J., Mentel, T.F., 2014. A large source of low-volatility secondary organic aerosol. Nature. 506, 476–479. https://ezproxy.cuc.edu.co:2067/10.1038/nature13032.

Feng, B., Li, L., Xu, H., Wang, T., Wu, R., Chen, J., Zhang, Y., Liu, S., Ho, S.S.H., Huang, W., 2019. $PM_{2.5}$-bound polycyclic aromatic hydrocarbons (PAHs) in Beijing: Seasonal variations, sources, and risk assessment. J. Environ. Sci. 77, 11–19. https://doi.org/10.1016/j.jes.2017.12.025.

Fernández-Camacho, R., Rodríguez, S., de la Rosa, J., Sánchez de la Campa, A.M., Alastuey, A., Querol, X., González-Castanedo, Y., Garcia-Orellana, I., Nava, S., 2012. Ultrafine particle and fine trace metal (As, Cd, Cu, Pb and Zn) pollution episodes induced by industrial emissions in Huelva, SW Spain. Atmos. Environ. 61, 507–517. https://doi.org/10.1016/j.atmosenv.2012.08.003.

Fleischer, N.L., Merialdi, M., van Donkelaar, A., Vadillo-Ortega, F., Martin, R.V., Betran, A.P., Souza, J.P., O'Neill, M.S., 2014. Outdoor air pollution, preterm birth, and low birth weight: Analysis of the world health organization global survey on maternal and perinatal health. Environ. Health Perspect. 122 (4), 425–430. https://doi.org/10.1289/ehp.1306837.

Forti, L., Jeuland, N., Raux, S., Pasquereau, M., 2005. Analysis of the particulates emitted by internal combustion engines. Oil Gas Sci. Technol 60 (6), 995–1011. https://doi.org/10.2516/ogst:2005070.

Gao, R., Sang, N., 2020. Quasi-ultrafine particles promote cell metastasis via HMGB1-mediated cancer cell adhesion. Environ. Pollut. 256, 113390. https://doi.org/10.1016/j.envpol.2019.113390.

Gao, D., Ripley, S., Weichenthal, S., Godri Pollitt, K.J., 2020. Ambient particulate matter oxidative potential: Chemical determinants, associated health effects, and strategies for risk management. Free Radic. Biol. Med. 151, 7–25. https://doi.org/10.1016/j.freeradbiomed.2020.04.028.

Garcia, K.O., Teixeira, E.C., Agudelo-Castañeda, D.M., Braga, M., Alabarse, P.G., Wiegand, F., Kautzmann, R.M., Silva, L.F., 2014. Assessment of nitro-polycyclic aromatic hydrocarbons in pm1 near an area of heavy-duty traffic. Sci. Total Environ. 479-480, 57–65. https://doi.org/10.1016/j.scitotenv.2014.01.126.

Gasparotto, J., Chaves, P.R., Da Boit, M.K., Da Rosa-Siva, H., Bortolin, R., Silva, L.F.O., Rabelo, T., Da Silva, J., Da Silva, F., Nordin, A., Soares, K., Borges, M., Gelain, D., Moreira, J., 2018. Obese rats are more vulnerable to inflammation, genotoxicity and oxidative stress induced by coal dust inhalation than non-obese rats. Ecotoxicol. Environ. Saf. 165, 44–51. https://doi.org/10.1016/j.ecoenv.2018.08.097.

Gasparotto, J., Da Boit, M.K., 2020. Coal as an energy source and its impacts on human health. Energy Geoscience https://doi.org/10.1016/j.engeos.2020.07.003 In press.

Gasparotto, J., Rodrigues, C.P., Da Boit, M.K., Silva, O.L.F., Gelain, D.P., Fonseca, M.J.C., 2019. Obesity associated with coal ash inhalation triggers systemic inflammation and oxidative damage in the hippocampus of rats. Food Chem. Toxicol. 133, 110766. https://doi.org/10.1016/j.fct.2019.110766.

Goel, A., Kumar, P., 2015. Characterisation of nanoparticle emissions and exposure at traffic intersections through fast-response mobile and sequential measurements. Atmos. Environ. 107, 374–390. https://doi.org/10.1016/j.atmosenv.2015.02.002.

Gómez-Ugalde, R., 2003. Efectos de la contaminación atmosférica en poblaciones de pequeños roedores silvestres (Microtus mexicanus, Peromyscus Melanotis y Peromiscus Difficilis) en México. D. F. Ph.D. Thesis. Universitat de Barcelona, p. 415. https://core.ac.uk/download/pdf/19919452.pdf.

González, L.T., Longoria Rodríguez, F.E., Sánchez-Domínguez, M., Cavazos, A., Leyva-Porras, C., Silva-Vidaurri, L.G., Acuña Askar, K., Kharissov, B.I., Villareal Chiu, J.F., Alfaro Barbosa, J.M., 2017. Determination of trace metals in TSP and $PM_{2.5}$ materials collected in the Metropolitan Area of Monterrey, Mexico: A characterization study by XPS, ICP-AES and SEM-EDS. Atmos. Res. 196, 8–22. https://doi.org/10.1016/j.atmosres.2017.05.009.

Gonzalez-Moragas, L., Roig, A., Laromaine, A., 2015. C. elegans as a tool for in vivo nanoparticle assessment. Adv. Colloid Interface Sci. 219, 10–26. https://doi.org/10.1016/j.cis.2015.02.001.

Grana, M., Toschi, N., Vicentini, L., Pietroiusti, A., Magrini, A., 2017. Exposure to ultrafine particles in different transport modes in the city of Rome. Environ. Pollut. 228, 201–210. https://doi.org/10.1016/j.envpol.2017.05.032.

Guo, L., Johnson, G.R., Hofmann, W., Wang, H., Morawska, L., 2019. Deposition of ambient ultrafine particles in the respiratory tract of children: a novel experimental method and its application. J. Aerosol Sci. 139, 105465. https://doi.org/10.1016/j.jaerosci.2019.105465.

Habre, R., Zhou, H., Eckel, S.P., Enebish, T., Fruin, S., Bastain, T., Rappatort, E., Gilliland, F., 2018. Short-term effects of airport-associated ultrafine particle exposure on lung function and inflammation in adults with asthma. Environ. Int. 118, 48–59. https://doi.org/10.1016/j.envint.2018.05.031.

HEI, 2013. Understanding the Health Effects of Ambient Ultrafine Particles. HEI Review Panel on Ultrafine Particles. HEI Perspectives 3. Health Effects Institute (HEI) https://www.healtheffects.org/system/files/Perspectives3.pdf.

Heusinkveld, H.J., Wahle, T., Campbell, A., Westerink, R.H.S., Tran, L., Johnston, H., Stone, V., Cassee, F.R., Schins, R.P.F., 2016. Neurodegenerative and neurological disorders by small inhaled particles. NeuroToxicology 56, 94–106. https://doi.org/10.1016/j.neuro.2016.07.007.

Hofman, J., Samson, R., Joosen, S., Blust, R., Lenaerts, S., 2018. Cyclist exposure to black carbon, ultrafine particles and heavy metals: An experimental study along two commuting routes near Antwerp. Belgium. Environ. Res. 164, 530–538. https://doi.org/10.1016/j.envres.2018.03.004.

Islam, N., Rabha, S., Silva, L.F.O., Saikia, B.K., 2019. Air quality and PM10-associated polyaromatic hydrocarbons around the railway traffic area: statistical and air mass trajectory approaches. Environ. Geochem. Health 41, 2039–2053. https://doi.org/10.1007/s10653-019-00256-z.

Jantzen, K., Møller, P., Karottki, D.G., Olsen, Y., Bekö, G., Clausen, G., Hersoug, L.G., Loft, S., 2016. Exposure to ultrafine particles, intracellular production of reactive oxygen species in leukocytes and altered levels of endothelial progenitor cells. Toxicology 359-360, 11–18. https://doi.org/10.1016/j.tox.2016.06.007.

Jeong, C.H., Traub, A., Evans, G.J., 2017. Exposure to ultrafine particles and black carbon in diesel-powered commuter trains. Atmos. Environ. 155, 46–52. https://doi.org/10.1016/j.atmosenv.2017.02.015.

De Jesus, A.L., Rahman, M.M., Mazaheri, M., Thompson, H., Knibbs, L.D., Jeong, C., Evans, G., Nei, W., Ding, A., Liping, Q., Li, L., Portin, H., Niemi, J.V., Timonen, H., Luoma, K., Petäjä, T., Kulmala, M., Kowalski, M., Peters, A., Cyrys, J., Ferrero, L., Manigrasso, M., Avino, P., Buonano, G., Reche, C., Querol, X., Beddows, D., Harrison, R.M., Sowlat, M.H., Sioutas, C., Morawska, L., 2019. Ultrafine particles and $PM_{2.5}$ in the air of cities around the world: Are they representative of each other? Environ. Int. 129, 118–135. https://doi.org/10.1016/j.envint.2019.05.021.

Jones, A.M., Harrison, R.M., 2016. Emission of ultrafine particles from the incineration of municipal solid waste: A review. Atmos. Environ. 140, 519–528. https://doi.org/10.1016/j.atmosenv.2016.06.005.

Kecorius, S., Kivekäs, N., Kristensson, A., Tuch, T., Covert, D.S., Birmili, W., Lihavainen, H., Hyvärinen, A.P., Martinsson, J., Sporre, M.K., Swietlicki, E., Wiedensohler, A., Ulevicius, V., 2016. Significant increase of aerosol number concentrations in air masses crossing a densely trafficked sea area. Oceanologia 58 (1), 1–12. https://doi.org/10.1016/j.oceano.2015.08.001.

Kelly, F.J., Fussell, J.C., 2012. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. Atmos. Environ. 60, 504–526. https://doi.org/10.1016/j.atmosenv.2012.06.039.

Keuken, M.P., Moerman, M., Zandveld, P., Henzing, J.S., 2015. Total and size-resolved particle number and black carbon concentrations near an industrial area. Atmos. Environ. 122, 196–205. https://doi.org/10.1016/j.atmosenv.2015.09.047.

Kim, K.H.H., Jahan, S.A., Kabir, E., Brown, R.J.C.C., 2013. A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. Environ. Int. 60, 71–80. https://doi.org/10.1016/j.envint.2013.07.019.

Kim, H.L., Han, J., Lee, S.M., Kwon, H.B., Hwang, J., Kim, Y.J., 2018. MEMS-based particle detection system for measuring airborne ultrafine particles. Sens. Actuator A. Phys. 283, 235–244. https://doi.org/10.1016/j.sna.2018.09.060.

Klaassen, C.D., 2013. Casarett and Doull's: Toxicology, The basic science of poison (English Editon). Mc Graw Hill Education – Medical, USA, pp. 525–907 ISBN: 978-0-07-176922-8.

Koçak, M., Mihalopoulos, N., Kubilay, N., 2007. Contributions of natural sources to high PM_{10} and $PM_{2.5}$ events in the eastern Mediterranean. Atmos. Environ. 41 (18), 3806–3818. https://doi.org/10.1016/j.atmosenv.2007.01.009.

Kumar, P., Robins, A., Vardoulakis, S., Britter, R., 2010. A review of the characteristics of nanoparticles in the urban atmosphere and the prospects for developing

regulatory controls. Atmos. Environ. 44 (39), 5035–5052. https://doi.org/10.1016/j.atmosenv.2010.08.016.

Kronbauer, M.A., Izquierdo, M., Dai, S., Wannders, F.B., Wagner, N.J., Mastalerz, M., Hower, J.C., Oliverira, M.L.S., Taffarel, S.R., Bizani, D., Silva, L.F.O., 2013. Geochemistry of ultrafine and nano-compounds in coal gasification ashes: A synoptic view. Sci. Total Environ. 456-457, 95–103. https://doi.org/10.1016/j.scitotenv.2013.02.066.

Kumar, P., Ketzel, M., Vardoulakis, S., Pirjola, L., Britter, R., 2011. Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment-A review. J. Aerosol Sci. 42 (9), 580–603. https://doi.org/10.1016/j.jaerosci.2011.06.001.

Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., Harrison, R.M., Norford, L., Britter, R., 2014. Ultrafine particles in cities. Environ. Int. 66, 1–10. https://doi.org/10.1016/j.envint.2014.01.013.

Kumar, P., Wiedensohler, A., Birmili, W., Quincey, P., Hallquist, M., 2016. Ultrafine Particles Pollution and Measurements. Compr. Anal. Chem. 73, 369–390. https://doi.org/10.1016/bs.coac.2016.04.004.

Kumar, P., Patton, A.P., Durant, J.L., Frey, H.C., 2018. A review of factors impacting exposure to $PM_{2.5}$, ultrafine particles and black carbon in Asian transport microenvironments. Atmos. Environ. 187, 301–316. https://doi.org/10.1016/j.atmosenv.2018.05.046.

Kwon, H.S., Ryu, M.H., Carlsten, C., 2020. Ultrafine particles: unique physicochemical properties relevant to health and disease. Exp. Mol. Med. 52 (3), 318–328. https://doi.org/10.1038/s12276-020-0405-1.

Landkocz, Y., Ledoux, F., André, V., Cazier, F., Genevray, P., Dewaele, D., Martin, P.J., Lepers, C., Verdin, A., Courcot, L., Boushina, S., Sichel, F., Gualtieri, M., Shirali, P., Courcot, D., Billet, S., 2017. Fine and ultrafine atmospheric particulate matter at a multi-influenced urban site: Physicochemical characterization, mutagenicity and cytotoxicity. Environ. Pollut. 221, 130–140. https://doi.org/10.1016/j.envpol.2016.11.054.

Lanzinger, S., Schneider, A., Breitner, S., Stafoggia, M., Erzen, I., Dostal, M., Pastorkova, A., Bastian, S., Cyrys, J., Zscheppang, A., Kolodnitska, T., Peters, A., Mykhalchuk, B., 2016. Associations between ultrafine and fine particles and mortality in five central European cities - Results from the UFIREG study. Environ. Int. 88, 44–52. https://doi.org/10.1016/j.envint.2015.12.006.

Lavigne, E., Lima, I., Hatzopoulou, M., Van Ryswyk, K., Decou, M.L., Luo, W., van Donkelaar, A., Martin, R.V., Chen, H., Stieb, D.M., Crighton, E., Gasparrini, A., Elten, M., Yasseen III, A.S., Burnett, R.T., Walker, M., Weichenthal, S., 2019. Spatial variations in ambient ultrafine particle concentrations and risk of congenital heart defects. Environ. Int. 130, 104953. https://doi.org/10.1016/j.envint.2019.104953.

Lee, W., Bell, M.L., Gasparrini, A., Armstrong, B.G., Sera, F., Hwang, S., Lavigne, E., Zanobetti, A., Coelho, M.S.Z.S., Saldiva, P.H.N., Osorio, S., Tobias, A., Zeka, A., Goodman, P.G., Forsberg, B., Rocklöv, J., Hashizume, M., Honda, Y., Guo, Y.L.L., Seposo, X., Dung, D.V., Dang, T.N., Tong, S., Guo, Y., Kim, H., 2017. Mortality burden of diurnal temperature range and its temporal changes : A multi-country study. Environ. Int. 110, 123–130. https://doi.org/10.1016/j.envint.2017.10.018.

León-Mejía, G., Silva, L.F., Civeira, M.S., Oliveira, M.L.S., Machado, M., Villela, I.V., Hartmann, A., Premoli, S., Corrêa, D.S., Silva, L., Henriques, J.A.P., 2016. Cytotoxicity and genotoxicity induced by coal and coal fly ash particles samples in V79 cells. Environ. Sci. Pollut. Res. 23, 24019–24031. https://ezproxy.cuc.edu.co:2067/10.1007/s11356-016-7623-z.

León-Mejía, G., Machado, M.N., Okuro, R.T., Silva, L.F., Telles, C., Dias, J., Niekraszewicz, L., Da Silva, J., Henriques, J.A.P., Zin, W.A., 2018. Intratracheal instillation of coal and coal fly ash particles in mice induces DNA damage and translocation of metals to extrapulmonary tissues. Sci. Total Environ. 625, 589–599. https://doi.org/10.1016/j.scitotenv.2017.12.283.

Li, Y., Yang, M., Meng, T., Niu, Y., Dai, Y., Zhang, L., Zheng, X., Jalava, P., Dong, G., Gao, W., Zheng, Y., 2020. Oxidative stress induced by ultrafine carbon black particles can elicit apoptosis in vivo and vitro. Sci. Total Environ. 709, 135802. https://doi.org/10.1016/j.scitotenv.2019.135802.

Liati, A., Schreiber, D., Arroyo Rojas Dasilva, Y., Dimopoulos Eggenschwiler, P., 2018. Ultrafine particle emissions from modern Gasoline and Diesel vehicles: An electron microscopic perspective. Environ. Pollut. 239, 661–669. https://doi.org/10.1016/j.envpol.2018.04.081.

Liu, J.Y., Hsiao, T.C., Lee, K.Y., Chuang, H.C., Cheng, T.J., Chuang, K.J., 2018. Association of ultrafine particles with cardiopulmonary health among adult subjects in the urban areas of northern Taiwan. Sci. Total Environ. 627, 211–215. https://doi.org/10.1016/j.scitotenv.2018.01.218.

Lopes, M., Russo, A., Monjardino, J., Gouveia, C., Ferreira, F., 2019. Monitoring of ultrafine particles in the surrounding urban area of a civilian airport. Atmos. Pollut. Res. 10 (5), 1454–1463. https://doi.org/10.1016/j.apr.2019.04.002.

Louis, C., Liu, Y., Tassel, P., Perret, P., Chaumond, A., André, M., 2016. PAH, BTEX, carbonyl compound, black-carbon, NO_2 and ultrafine particle dynamometer bench emissions for Euro 4 and Euro 5 diesel and gasoline passenger cars. Atmos. Environ. 141, 80–95. https://doi.org/10.1016/j.atmosenv.2016.06.055.

Lü, S., Zhang, R., Yao, Z., Yi, F., Ren, J., Wu, M., Feng, M., Wang, Q., 2012. Size distribution of chemical elements and their source apportionment in ambient coarse, fine, and ultrafine particles in Shanghai urban summer atmosphere. J. Environ. Sci. 24 (5), 882–890. https://doi.org/10.1016/S1001-0742(11)60870-X.

Lü, S., Hao, X., Liu, D., Wang, Q.Q., Zhang, W., Liu, P., Zhang, R., Yu, S., Pan, R., Wu, M., Yonemochi, S., Wang, Q., 2016. Mineralogical characterization of ambient fine/ultrafine particles emitted from Xuanwei C1 coal combustion. Atmos. Res. 169, 17–23. https://doi.org/10.1016/j.atmosres.2015.09.020.

Luengo-Oroz, J., Reis, S., 2019. Assessment of cyclists' exposure to ultrafine particles along alternative commuting routes in Edinburgh. Atmos. Pollut. Res. 10 (4), 1148–1158. https://doi.org/10.1016/j.apr.2019.01.020.

Lundborg, M., Johard, U., Låstbom, L., Gerde, P., Camner, P., 2001. Human alveolar macrophage phagocytic function is impaired by aggregates of ultrafine carbon particles. Environ. Res. 86 (3), 244–253. https://doi.org/10.1006/enrs.2001.4269.

Ma, N., Birmili, W., 2015. Estimating the contribution of photochemical particle formation to ultrafine particle number averages in an urban atmosphere. Sci Total Environ. 512-513, 154–166. https://doi.org/10.1016/j.scitotenv.2015.01.009.

Magalhaes, S., Baumgartner, J., Weichenthal, S., 2018. Impacts of exposure to black carbon, elemental carbon, and ultrafine particles from indoor and outdoor sources on blood pressure in adults: A review of epidemiological evidence. Environ. Res. 161, 345–353. https://doi.org/10.1016/j.envres.2017.11.030.

Maji, S., Ahmed, S., Siddiqui, W.A., Ghosh, S., 2017. Short term effects of criteria air pollutants on daily mortality in Delhi. India. Atmos. Environ. 150, 210–219. https://doi.org/10.1016/j.atmosenv.2016.11.044.

Marabini, L., Ozgen, S., Turacchi, S., Aminti, S., Arnaboldi, F., Lonati, G., Fermo, P., Corbella, L., Valli, G., Bernardoni, V., Dell'Acqua, M., Vecchi, R., Becagli, S., Caruso, D., Corrado, G.L., Marinovich, M., 2017. Ultrafine particles (UFPs) from domestic wood stoves: genotoxicity in human lung carcinoma A549 cells. Mutat. Res. Genet. Toxicol. Environ. Mutagen. 820, 39–46. https://doi.org/10.1016/j.mrgentox.2017.06.001.

Marimon-Bolívar, W., Tejeda-Benítez, L.P., Núñez-Avilés, C.A., De Léon-Pérez, D.D., 2019. Evaluation of the in vivo toxicity of green magnetic nanoparticles using Caenorhabditis elegans as a biological model. Environ. Nanotechnol. Monit. Manag. 12, 100253. https://doi.org/10.1016/j.enmm.2019.100253.

Martinello, K., Oliveira, M., Molossi, F., Ramos, C., Teixeira, E., Kautzmann, R., Silva, L.F., 2014. Direct identification of hazardous elements in ultra-fine and nanominerals from coal fly ash produced during diesel co-firing. Sci. Total Environ. 470-471, 444–452. https://doi.org/10.1016/j.scitotenv.2013.10.007.

Martins, V., Correia, C., Cunha-Lopes, I., Faria, T., Diapouli, E., Manousakas, M.I., Eleftheriadis, K., Almeida, S.M., 2021. Chemical characterisation of particulate matter in urban transport modes. J. Environ. Sci. 100, 51–61. https://doi.org/10.1016/j.jes.2020.07.008.

Miller, B.G., 2011. 9 - Emissions Control Strategies for Power Plants. In: Miller, B.G. (Ed.), Clean Coal Engineering Technology. Elsevier, Amsterdam, pp. 375–481 https://doi.org/10.1016/b978-1-85617-710-8.00009-1.

Miller, M.R., Shaw, C.A., Langrish, J.P., 2012. From particles to patients: Oxidative stress and the cardiovascular effects of air pollution. Future Cardiol. 8 (4), 577–602. https://doi.org/10.2217/fca.12.43.

Mishra, R.K., Shukla, A., Parida, M., Pandey, G., 2016. Urban roadside monitoring and prediction of CO, NO_2 and SO_2 dispersion from on-road vehicles in megacity Delhi. Transp. Res. D Transp. Environ. 46, 157–165. https://doi.org/10.1016/j.trd.2016.03.019.

Møller, K.L., Brauer, C., Mikkelsen, S., Bonde, J.P., Loft, S., Helweg-Larsen, K., Thygesen, L.C., 2020. Cardiovascular disease and long-term occupational exposure to ultrafine particles: A cohort study of airport workers. Int. J. Hyg. Environ. Health 223 (1), 214–219. https://doi.org/10.1016/j.ijheh.2019.08.010.

Morawska, L., Ristovski, Z., Jayaratne, E.R., Keogh, D.U., Ling, X., 2008. Ambient nano and ultrafine particles from motor vehicle emissions: Characteristics, ambient processing and implications on human exposure. Atmos. Environ. 42 (35), 8113–8138. https://doi.org/10.1016/j.atmosenv.2008.07.050.

Morris-Schaffer, K., Sobolewski, M., Welle, K., Conrad, K., Yee, M., O'Reilly, M.A., Cory-Slechta, D.A., 2018. Cognitive flexibility deficits in male mice exposed to neonatal hyperoxia followed by concentrated ambient ultrafine particles. Neurotoxicol. Teratol. 70, 51–59. https://doi.org/10.1016/j.ntt.2018.10.003.

Muñoz-Salazar, J.I., Raga, G.B., Yakobi-Hancock, J., Kim, J.S., Rosas, D., Caudillo, L., Alvarez-Ospina, H., Ladino, L.A., 2020. Ultrafine aerosol particles in the western Caribbean: A first case study in Merida. Atmos. Pollut. Res. 11 (10), 1767–1775. https://doi.org/10.1016/j.apr.2020.07.008.

Nho, R., 2020. Pathological effects of nano-sized particles on the respiratory system. Nanomedicine : N. B.M. 29, 102242. https://doi.org/10.1016/j.nano.2020.102242.

Nyarku, M., Buonanno, G., Ofosu, F., Jayaratne, R., Mazaheri, M., Morawska, L., 2019. Schoolchildren's personal exposure to ultrafine particles in and near Accra. Ghana. Environ. Int. 133. https://doi.org/10.1016/j.envint.2019.105223.

Oberdörster, G., Sharp, Z., Atudorei, V., Elder, A., Gelein, R., Lunts, A., Kreyling, W., Cox, C., 2002. Extrapulmonary translocation of ultrafine carbon particles following whole-body inhalation exposure of rats. J. Toxicol. Environ. Health Part A. 65 (20), 1531–1543. https://doi.org/10.1080/00984100290071658.

Ohlwein, S., Kappeler, R., Kutlar Joss, M., Künzli, N., Hoffmann, B., 2019. Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence. Int. J. Public Health 64, 447–449. https://doi.org/10.1007/s00038-019-01202-7.

Oliveira, M.L.S., Navarro, O.G., Crissien, T.J., Tutikian, B.F., Da Boit, K., Texeira, E.C., Cabello, J.J., Agudelo-Castañeda, D.M., Silva, L.F.O., 2017. Coal emissions adverse human health effects associated with ultrafine/nano-particles role and resultant engineering controls. Environ. Res. 158, 450–455. https://doi.org/10.1016/j.envres.2017.07.002.

Oliveira, M.L.S., Izquierdo, M., Querol, X., Lieberman, R.N., Saikia, B.K., Silva, L.F.O., 2019a. Nanoparticles from Construction Wastes: A Problem to Health and the Environment. J. Clean. Prod. 219, 236–243. https://doi.org/10.1016/j.jclepro.2019.02.096.

Oliveira, M.L.S., Pinto, D., Tutikian, B.F., Da Boit, K., Saikia, B.K., Silva, L.F.O., 2019b. Pollution from uncontrolled coal fires: Continuous gaseous emissions and nanoparticles from coal mining industry. J. Clean. Prod. 215, 1140–1148. https://doi.org/10.1016/j.jclepro.2019.01.169.

Paunescu, A.C., Casas, M., Ferrero, A., Pañella, P., Bougas, N., Beydon, N., Just, J., Lezmi, J., Ballester, F., Momas, I., 2019. Associations of black carbon with lung function and airway inflammation in schoolchildren. Environ. Int. 131, 104984. https://doi.org/10.1016/j.envint.2019.104984.

Peralta, O., Ortínez-Alvarez, A., Basaldud, R., Santiago, N., Alvarez-Ospina, H., de la Cruz, K., Barrera, V., Espinosa, M.D.L.C., Saavedra, I., Castro, T., Martínez-Arroyo, A., Páramo, V.H., Ruíz-Suárez, L.G., Vazquez-Galvez, F.A., Gavilán, A., 2019. Atmospheric black carbon concentrations in Mexico. Atmos. Res. 230, 104626. https://doi.org/10.1016/j.atmosres.2019.104626.

Pétursdóttir, U., Kirkelund, G.M., Press-Kristensen, K., Hertel, O., Mikkelsen, T.N., 2018. Ultrafine particles in inhabited areas in the Arctic - From very low to high concentrations. Atmos. Pollut. Res. 9 (2), 299–308. https://doi.org/10.1016/j.apr.2017.10.008.

Platel, A., Privat, K., Talahari, S., Delobel, A., Dourdin, G., Gateau, E., Simar, S., Saleh, Y., Sotty, J., Antherieu, S., Canivet, L., Alleman, L.Y., Perdrix, E., Garçon, G., Denayer, F.O., Lo Guidice, J.M., Nesslany, F., 2020. Study of in vitro and in vivo genotoxic effects of air pollution fine ($PM_{2.5-0.18}$) and quasi-ultrafine ($PM_{0.18}$) particles on lung models. Sci. Total Environ 711, 134666. https://doi.org/10.1016/j.scitotenv.2019.134666.

Pourret, O., Hursthouse, A., 2019. It's time to replace the term "heavy metals" with "potentially toxic elements" when reporting environmental research. Int. J. Environ. Res. Public Health 16 (22), 4446. https://doi.org/10.3390/ijerph16224446.

Pyo, J., Ock, Y., Jeong, D., Park, K., Lee, D., 2017. Development of filter-free particle filtration unit utilizing condensational growth: With special emphasis on high-concentration of ultrafine particles. Build. Environ. 112, 200–208. https://doi.org/10.1016/j.buildenv.2016.11.011.

Ramírez, O., de la Sánchez, C.A.M., Amato, F., Moreno, T., Silva, L.F.O., de la Rosa, J., 2019. Physicochemical Characterization and Sources of the Thoracic Fraction of Road Dust in a Latin American Megacity. Sci. Total Environ. 652, 434–446. https://doi.org/10.1016/j.scitotenv.2018.10.214.

Ramírez, O., Da Boit, K., Blanco, E., Silva, L.F.O., 2020. Hazardous thoracic and ultrafine particles from road dust in a Caribbean industrial city. Urban Clim. 33, 100655. https://doi.org/10.1016/j.uclim.2020.100655.

Rengarajan, T., Rajendran, P., Nandakumar, N., Lokeshkumar, B., Rajendran, P., Nishigaki, I., 2015. Exposure to polycyclic aromatic hydrocarbons with special focus on cancer. Asian Pac. J. Trop. Biomed. 5, 182–189. https://doi.org/10.1016/S2221-1691(15)30003-4.

Ribeiro, J., Flores, D., 2020. Occurrence, leaching and mobility of trace elements in a coal mining waste dump: the case of Douro Coalfield (Portugal). Energy Geoscience https://doi.org/10.1016/j.engeos.2020.09.005 In press.

Ribeiro, J., Daboit, K., Flores, D., Kronbauer, M.A., Silva, L.F.O., 2013a. Extensive FE-SEM/EDS, HR-TEM/EDS and ToF-SIMS studies of micron- to nano-particles in anthracite fly ash. Sci. Total Environ. 452-453, 98–107. https://doi.org/10.1016/j.scitotenv.2013.02.010.

Ribeiro, J., Taffarel, S.R., Sampaio, C.H., Flores, D., Silva, L.F.O., 2013b. Mineral speciation and fate of some hazardous contaminants in coal waste pile from anthracite mining in Portugal. Int. J. Coal Geol. 109-110, 15–23. https://doi.org/10.1016/j.coal.2013.01.007.

Rizza, V., Stabile, L., Vistocco, D., Russi, A., Pardi, S., Buonanno, G., 2019. Effects of the exposure to ultrafine particles on heart rate in a healthy population. Sci. Total Environ. 650, 2403–2410. https://doi.org/10.1016/j.scitotenv.2018.09.385.

Rojas, J.C., Sánchez, N.E., Schneider, I., Teixeira, E.C., Silva, L.F.O., 2019. Exposure to nanometric pollutants in primary schools: Environmental implications. Urban Clim. 27, 412–419. https://doi.org/10.1016/j.uclim.2018.12.011.

Sade, M.Y., Novack, V., Ifergane, G., Horev, A., Kloog, I., 2015. Air pollution and ischemic stroke among young adults. Stroke 46 (12), 3348–3353. https://doi.org/10.1161/STROKEAHA.115.010992.

Saha, P.K., Zimmerman, N., Malings, C., Hauryliuk, A., Li, Z., Snell, L., Subramanian, R., Lipsky, E., Apte, J.S., Robinson, A.L., Presto, A.A., 2019. Quantifying high-resolution spatial variations and local source impacts of urban ultrafine particle concentrations. Sci. Total Environ. 655, 473–481. https://doi.org/10.1016/j.scitotenv.2018.11.197.

Saikia, B.K., Saikia, J., Rabha, S., Silva, L.F.O., Finkelman, R., 2018. Ambient nanoparticles/nanominerals and hazardous elements from coal combustion activity: Implications on energy challenges and health hazards. Geosci. Front. 9 (3), 863–875. https://doi.org/10.1016/j.gsf.2017.11.013.

Sanderson, P., Delgado-Saborit, J.M., Harrison, R.M., 2014. A review of chemical and physical characterisation of atmospheric metallic nanoparticles. Atmos. Environ. 94, 353–365. https://doi.org/10.1016/j.atmosenv.2014.05.023.

Santibáñez-Andrade, M., Quezada-Maldonado, E.M., Osornio-Vargas, Á., Sánchez-Pérez, Y., García-Cuellar, C.M., 2017. Air pollution and genomic instability: The role of particulate matter in lung carcinogenesis. Environ. Pollut. 229, 412–422. https://doi.org/10.1016/j.envpol.2017.06.019.

Schneider, I.L., Teixeira, E.C., Silva, L.F., Wiegand, F., 2015. Atmospheric particle number concentration and size distribution in a traffic-impacted area. Atmos. Pollut. Res. 6, 877–885. https://doi.org/10.5094/APR.2015.097.

Schneider, I.L., Teixeira, E.C., Agudelo-Castañeda, D., Silva, G., Balzaretti, N., Braga, M., Silva, L.F.O., 2016. FTIR analysis and evaluation of carcinogenic and mutagenic risks of nitro-polycyclic aromatic hydrocarbons in PM1.0. Sci. Total Environ. 541, 1151–1160. https://doi.org/10.1016/j.scitotenv.2015.09.142.

Seigneur, C., 2019. Atmospheric Dispersion. Air Pollution: Concepts, Theory, and Applications. Cambridge University Press, pp. 95–124 https://doi.org/10.1017/9781108674614.006.

Sharma, S., Kumar, M.S., Parmar, A., Sachar, S., 2018. Chapter 18 – Understanding toxicity of nanomaterials in the environment: crucial tread for controlling the production, processing, and assessing the risk. Nanomater. Chromatogr., 467–500 https://doi.org/10.1016/B978-0-12-812792-6.00018-2.

Shukla, A., Bunkar, N., Kumar, R., Bhargava, A., Tiwari, R., Chaudhury, K., Goryacheva, I.Y., Mishra, P.K., 2019. Air pollution associated epigenetic modifications: Transgenerational inheritance and underlying molecular mechanisms. Sci. Total Environ. 656, 760–777. https://doi.org/10.1016/j.scitotenv.2018.11.381.

Silva, L.F.O., Da Boit, K., Sampaio, C.H., Jasper, A., Andrade, M.L., Kostova, I.J., Waanders, F.B., Henke, K.R., Hower, J.C., 2012a. The occurrence of hazardous volatile elements and nanoparticles in Bulgarian coal fly ashes and the effect on human health exposure. Sci. Total Environ. 416, 513–526. https://doi.org/10.1016/j.scitotenv.2011.11.012.

Silva, L.F.O., Jasper, A., Andrade, M.L., Sampaio, C.H., Dai, S., Li, X., Li, T., Chen, W., Wang, X., Liu, H., Zhao, L., Hopps, S.G., Jewell, R.F., Hower, J.C., 2012b. Applied investigation on the interaction of hazardous elements binding on ultrafine and nanoparticles in Chinese anthracite-derived fly ash. Sci. Total Environ. 419, 250–264. https://doi.org/10.1016/j.scitotenv.2011.12.069.

Silva, L.F.O., Milanes, C., Pinto, D., Ramirez, O., Lima, B.D., 2020a. Multiple hazardous elements in nanoparticulate matter from a Caribbean industrialized atmosphere. Chemosphere 239, 124776. https://doi.org/10.1016/j.chemosphere.2019.124776.

Silva, L.F.O., Pinto, D., Neckel, A., Oliveira, M.L.S., Sampaio, C.H., 2020b. Atmospheric nanocompounds on Lanzarote Island: Vehicular exhaust and igneous geologic formation interactions. Chemosphere 254, 126822. https://doi.org/10.1016/j.chemosphere.2020.126822.

Simkhovich, B.Z., Kleinman, M.T., Kloner, R.A., 2008. Air Pollution and Cardiovascular Injury: Epidemiology, Toxicology, and Mechanisms. J. Am. Coll. Cardiol. 52 (9), 719–726. https://doi.org/10.1016/j.jacc.2008.05.029.

Sinis, S.I., Gourgoulianis, K.I., Hatzoglou, C., Zarogiannis, S.G., 2019. Mechanisms of engineered nanoparticle induced neurotoxicity in Caenorhabditis elegans. Environ. Toxicol. Pharmacol. 67, 29–34. https://doi.org/10.1016/j.etap.2019.01.010.

Slezakova, K., de Oliveira Fernandes, E., Pereira, M.D.C., 2019. Assessment of ultrafine particles in primary schools: Emphasis on different indoor microenvironments. Environ. Pollut. 246, 885–895. https://doi.org/10.1016/j.envpol.2018.12.073.

Song, H., Zhang, Y., Luo, M., Gu, J., Wu, M., Xu, D., Xu, G., Ma, L., 2019. Seasonal variation, sources and health risk assessment of polycyclic aromatic hydrocarbons in different particle fractions of PM2.5 in Beijing, China. Atmos. Pollut. Res. 10 (1), 105–114. https://doi.org/10.1016/j.apr.2018.06.012.

Soppa, V.J., Shinnawi, S., Hennig, F., Sasse, B., Hellack, B., Kaminski, H., Quass, U., Schins, R.P.F., Kuhlbusch, T.A.J., Hoffmann, B., 2019. Effects of short-term exposure to fine and ultrafine particles from indoor sources on arterial stiffness – A randomized sham-controlled exposure study. Int. J. Hyg. Environ. Health 222 (8), 1115–1132. https://doi.org/10.1016/j.ijheh.2019.08.002.

Srimuruganandam, B., Shiva Nagendra, S.M., 2011. Chemical characterization of PM_{10} and $PM_{2.5}$ mass concentrations emitted by heterogeneous traffic. Sci. Total Environ. 409 (17), 3144–3157. https://doi.org/10.1016/j.scitotenv.2011.04.042.

Stacey, B., 2019. Measurement of ultrafine particles at airports: A review. Atmos. Environ. 198, 463–477. https://doi.org/10.1016/j.atmosenv.2018.10.041.

Stacey, B., Harrison, R.M., Pope, F., 2020. Evaluation of ultrafine particle concentrations and size distributions at London Heathrow Airport. Atmos. Environ. 222, 117148. https://doi.org/10.1016/j.atmosenv.2019.117148.

Stafoggia, M., Schneider, A., Cyrys, J., Samoli, E., Andersen, Z.J., Bedada, G.B., Bellander, T., Cattani, G., Eleftheriadis, K., Faustini, A., Hoffmann, B., Jacquemin, B., Katsouyanni, K., Massling, A., Pekkanen, J., Perez, N., Peters, A., Quass, U., Yli-Tuomi, T., Forastiere, F., 2017. Association Between Short-term Exposure to Ultrafine Particles and Mortality in Eight European Urban Areas. Epidemiology 28 (2), 172–180. https://doi.org/10.1097/EDE.0000000000000599.

Sun, J., Birmili, W., Hermann, M., Tuch, T., Weinhold, K., Spindler, G., Schladitz, A., Bastian, S., Löschau, G., Cyrys, J., Gu, J., Flentje, H., Briel, B., Asbach, C., Kaminski, H., Ries, L., Sohmer, R., Gerwig, H., Wirtz, K., Meinhardt, F., Schwerin, A., Bath, O., Ma, N., Wiedensohler, A., 2019. Variability of black carbon mass concentrations, submicrometer particle number concentrations and size distributions: results of the German Ultrafine Aerosol Network ranging from city street to High Alpine locations. Atmos. Environ. 202, 256–268. https://doi.org/10.1016/j.atmosenv.2018.12.029.

Sydbom, A., Blomberg, A., Parnia, S., Stenfors, N., Sandström, T., Dahle, S.E., 2001. Health effects of diesel exhaust emissions. Eur. Respir. J. 17, 733–746. https://doi.org/10.1183/09031936.01.17407330.

Thurston, G.D., Ito, K., Lall, R., 2011. A source apportionment of U.S. fine particulate matter air pollution. Atmos. Environ. 45 (24), 3924–3936. https://doi.org/10.1016/j.atmosenv.2011.04.070.

Timbrell, J.A., 2009. Principles of Biochemical Toxicology. Fourth edition. Informa Healthcare USA, New York.

Topinka, J., Milcova, A., Schmuczerova, J., Krouzek, J., Hovorka, J., 2013. Ultrafine particles are not major carriers of carcinogenic PAHs and their genotoxicity in size-segregated aerosols. Mutat. Res. Genet. Toxicol. Environ. Mutagen. 754 (1-2), 1–6. https://doi.org/10.1016/j.mrgentox.2012.12.016.

Tran, P.T.M., Ngoh, J.R., Balasubramanian, R., 2020. Assessment of the integrated personal exposure to particulate emissions in urban micro-environments: A pilot study. Aerosol Air Qual Res. 20 (2), 341–357. https://10.4209/aaqr.2019.04.0201.

Vallero, D.A., 2011. 18 - Air Pollution: Atmospheric Wastes. In: Letcher, T.M., Vallero, D.A. (Eds.), Waste: A Handbook for Management. Elsevier, Amsterdam, pp. 243–264 https://doi.org/10.1016/B978-0-12-381475-3.10018-X.

Van den Bossche, J., Peters, J., Verwaeren, J., Botteldooren, D., Theunis, J., De Baets, B., 2015. Mobile monitoring for mapping spatial variation in urban air quality: Development and validation of a methodology based on an extensive dataset. Atmos. Environ. 105, 148–161. https://10.1016/j.atmosenv.2015.01.017.

Wahlang, B., Jin, J., Bier, J.I., Hardesty, J.E., Daly, E.F., Schnegelberger, R.D., Falkner, C.K., Prough, R.A., Kirpich, I.A., Cave, M.C., 2019. Mechanisms of environmental contributions to fatty liver disease. Curr. Environ. Health Rep. 6, 80–94. https://doi.org/10.1007/s40572-019-00232-w.

Wardoyo, A.Y.P., Juswono, U.P., Noor, J.A.E., 2018. Varied dose exposures to ultrafine particles in the motorcycle smoke cause kidney cell damages in male mice. Toxicol. Rep. 5, 383–389. https://doi.org/10.1016/j.toxrep.2018.02.014.

Wei, H., Feng, Y., Liang, F., Cheng, W., Wu, X., Zhou, R., Wang, Y., 2017. Role of oxidative stress and DNA hydroxymethylation in the neurotoxicity of fine particulate matter. Toxicology 380, 94–103. https://doi.org/10.1016/j.tox.2017.01.017.

Weichenthal, S., Van Ryswyk, K., Goldstein, A., Shekarrizfard, M., Hatzopoulou, M., 2016. Characterizing the spatial distribution of ambient ultrafine particles in Toronto, Canada: A land use regression model. Environ. Pollut. 208, 241–248. https://10.1016/j.envpol.2015.04.011.

WHO, 2006. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: global update 2005: summary of risk assessment. World Health Organization (WHO) https://apps.who.int/iris/handle/10665/69477. (Accessed 30 September 2020).

Wong, B.S.E., Hu, Q., Baeg, G.H., 2017. Epigenetic modulations in nanoparticle-mediated toxicity. Food Chem. Toxicol. 109, 746–752. https://doi.org/10.1016/j.fct.2017.07.006.

Wu, T., Xu, H., Liang, X., Tang, M., 2019. Caenorhabditis elegans as a complete model organism for biosafety assessments of nanoparticles. Chemosphere 221, 708–726. https://doi.org/10.1016/j.chemosphere.2019.01.021.

Xia, M., Harb, H., Saffari, A., Sioutas, C., Chatila, T.A., 2018. A Jagged 1–Notch 4 molecular switch mediates airway inflammation induced by ultrafine particles. J. Allergy Clin. Immunol. 142 (4), 1243–1256. https://doi.org/10.1016/j.jaci.2018.03.009.

Xiao, X., Cao, L., Wang, R., Shen, Z.X., Cao, Y.X., 2016. Airborne fine particulate matter alters the expression of endothelin receptors in rat coronary arteries. Environ. Pollut. 218, 487–496. https://doi.org/10.1016/j.envpol.2016.07.028.

Yadav, I.C., Linthoingambi, N.D., Kumar, V.S., Li, J., Zhang, G., 2018. Concentrations, sources and health risk of nitrated- and oxygenated-polycyclic aromatic hydrocarbon in urban indoor air and dust from four cities of Nepal. Sci. Total Environ. 643, 1013–1023. https://doi.org/10.1016/j.scitotenv.2018.06.265.

Yang, B., Li, X., Chen, D., Xiao, C., 2017a. Effects of fine air particulates on gene expression in non-small-cell lung cancer. Adv. Med. Sci. 62 (2), 295–301. https://doi.org/10.1016/j.advms.2016.12.003.

Yang, L., Hou, X.Y.Y., Wei, Y., Thai, P., Chai, F., 2017b. Biomarkers of the health outcomes associated with ambient particulate matter exposure. Sci. Total Environ. 579, 1446–1459. https://doi.org/10.1016/j.scitotenv.2016.11.146.

Zamberland, D.C., Halmenschelager, P.T., Silva, L.F.O., Da Rocha, A., Rocha, J.B.T., 2020. Copper decreases associative learning and memory in Drosophila melanogaster. Sci. Total Environ 710, 135306. https://doi.org/10.1016/j.scitotenv.2019.135306.

Zhang, W., Lei, T., Lin, Z.Q., Zhang, H.S., Yang, D.F., Xi, Z.G., Chen, J.H., Wang, W., 2011. Pulmonary toxicity study in rats with PM_{10} and $PM_{2.5}$: Differential responses related to scale and composition. Atmos. Environ. 45 (4), 1034–1041. https://doi.org/10.1016/j.atmosenv.2010.10.043.

Zhang, L., Guo, C., Jia, X., Xu, H., Pan, M., Xu, D., Shen, X., Zhang, J., Tan, J., Qian, H., Dong, C., Shi, Y., Zhou, X., Wu, C., 2018b. Personal exposure measurements of school- children to fine particulate matter (PM2.5) in winter of 2013, Shanghai, China. PLoS ONE 13 (4), e0193586. https://doi.org/10.1371/journal.pone.0193586.

Zhang, Y., Dong, S., Wang, H., Tao, S., Kiyama, R., 2016. Biological impact of environmental polycyclic aromatic hydrocarbons (ePAHs) as endocrine disruptors. Environ. Pollut. 213, 809–824. https://doi.org/10.1016/j.envpol.2016.03.050.

Zhang, H.H., Li, Z., Liu, Y., Xinag, P., Cui, X.Y., Ye, H., Hu, B.L., Lou, L.P., 2018. Physical and chemical characteristics of $PM_{2.5}$ and its toxicity to human bronchial cells BEAS-2B in the winter and summer. J. Zhejiang Univ. Sci B 19 (4), 317–326. https://doi.org/10.1631/jzus.B1700123.

Zhang, Y., Tu, B., Jiang, X., Xu, G., Liu, X., Tang, Q., Bai, L., Meng, P., Zhang, L., Qin, X., Zou, Z., Chen, C., 2019. Exposure to carbon black nanoparticles during pregnancy persistently damages the cerebrovascular function in female mice. Toxicology 422, 44–52. https://doi.org/10.1016/j.tox.2019.04.014.

Zhang, L., Yang, L., Zhou, Q., Zhang, X., Xing, W., Wei, Y., Hu, M., Zhao, L., Toriba, A., Hayakawa, K., Tang, N., 2020. Size distribution of particulate polycyclic aromatic hydrocarbons in fresh combustion smoke and ambient air: A review. J. Environ. Sci. 88, 370–384. https://doi.org/10.1016/j.jes.2019.09.007.

Zhao, Y., Lin, Z., Jia, R., Li, G., Xi, Z., Wang, D., 2014. Transgenerational effects of traffic-related fine particulate matter ($PM_{2.5}$) on nematode Caenorhabditis elegans. J. Hazardous Mater. 274, 106–114. https://doi.org/10.1016/j.jhazmat.2014.03.064.

Zhao, Y., Wang, F., Zhao, J., 2015. Size-resolved ultrafine particle deposition and Brownian coagulation from gasoline vehicle exhaust in an environmental test chamber. Environ. Technol. 49, 12153–12160. https://doi.org/10.1021/acs.est.5b02455.

Zhou, S., Yuan, Q., Li, W., Lu, Y., Zhang, Y., Wang, W., 2014. Trace metals in atmospheric fine particles in one industrial urban city: Spatial variations, sources, and health implications. J. Environ. Sci. 26 (1), 205–213. https://doi.org/10.1016/S1001-0742(13)60399-X.